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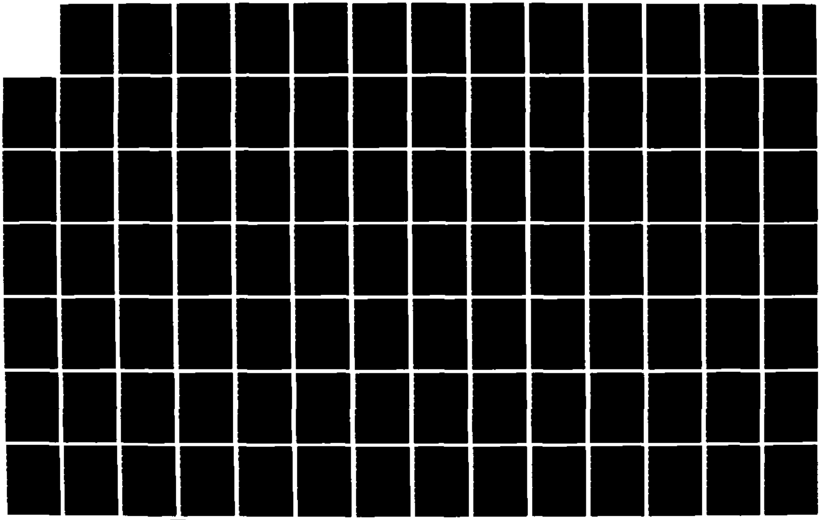

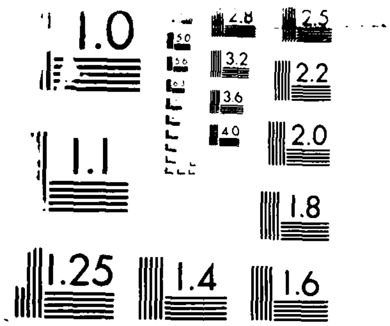
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AN EVALUATION AND PROPOSAL OF
UNITED STATES AIR FORCE USES OF
ROLLER COMPACTED CONCRETE PAVEMENT

THESIS

Scott K. Borges
Captain, USAF, PE

AFIT/GEM/DET/86S-3

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AN EVALUATION AND PROPOSAL OF UNITED STATES AIR FORCE USES OF ROLLER COMPACTED CONCRETE PAVEMENT

THESIS

Presented to the Faculty of the School of Systems and

Logistics of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering Management

Scott K. Borges, B.S.

Captain, USAF, PE

September 1986

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Scott K. Borges

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Abstract

This research project studied the possibility of Roller Compacted Concrete Pavement (RCCP) use by the United States Air Force, RCCP is a dry, zero-slump concrete paving mixture. The low cost, high strength, and quick placement of RCCP make it extremely attractive as an alternate construction and repair method for USAF pavements.

This project accomplished five objectives. First, a thorough review of the literature provided a list of the advantages and disadvantages of RCCP. Second, a survey determined the RCCP knowledge level of a small group of USAF Pavement Engineers. Third, another survey established the relative importance of certain pavement characteristics in various USAF pavement applications. Fourth, a decision support model was created to assist in the selection of candidate U.S. Air Force RCCP projects. Finally, using this model, the Strategic Air Command project database was searched to provide a list of recommended RCCP projects.

AN EVALUATION AND PROPOSAL OF UNITED STATES AIR FORCE USES OF ROLLER COMPACTED CONCRETE PAVEMENT

I. Introduction

Overview

The United States Air Force owns and operates approximately 500 million square yards of pavement. That is an area 300 feet wide and 2840 miles long. Think of it as a runway from Washington DC to Los Angeles, California. The total replacement value of USAF pavements is in excess of 20 billion dollars. This amount accounts for 20 percent of all USAF facility inventory (10:ST-1).

According to Colonel John Choate, Chief of the Air Staff Engineering and Services Plans Division, 75 to 80 percent of US Air Force Pavements are already beyond their design life (5). This level of pavement degradation, coupled with the high real property value of USAF pavements, highlights the potential value of an improvement in pavement maintenance and construction.

Approximately half of USAF pavement are constructed of Portand Cement Concrete (PCC). PCC is a requirement for all heavy load runway pavements as well as most aircraft parking and taxi areas (11:2-4).

Traditionally, PCC pavements have been constructed with the use of wooden or metal forms. Skilled engineers and craftsmen are required to lay out the forming system and

place the PCC. This process is both time and labor intensive. The continuing requirement to "do more with less" mandates that the engineering community search for better methods to accomplish their mission; in this case, the construction of PCC pavements. Roller Compacted Concrete Pavement (RCCP) could be an answer to that mandate.

RCCP is a new technology in pavements. Originally developed in Europe, it is a much simpler and less expensive method of placing PCC. David Pittman explains the unique characteristics of RCCP as follows:

> RCCP consists of a concrete mixture that typically has a lower water and paste content than conventional concrete paving mixtures. Since RCC is a zero-slump concrete, just enough water is added to the mixture so that adequate consolidation or density can be achieved with the rollers. The lower water content and high density of RCCP have resulted in flexural strengths in excess of 1000 psi in mixtures designed for 650 psi (37:428).

The concrete for RCC pavements is hauled to the site in standard dump trucks and placed using a slightly modified asphalt paving machine. Once in place, the mixture is rolled by standard asphalt vibratory and rubber-tired rollers. Curing methods vary.

Clearly, RCCP is easier and quicker to construct than standard PCC. RCCP is also less expensive. In several cases in which RCCP was allowed as an alternate, it was bid even lower than asphalt. If RCCP continues to develop, USAF Pavement Engineers may be forced to deal with contractors requesting Value Engineering consideration using RCCP.

On 22 April 1985, Colonel Robert L. Klingensmith, Acting Assistant Director of USAF Engineering and Services, signed a letter to all Major Commands concerning Roller Compacted Concrete Pavement. The letter said, in part:

> I highly recommend that you give serious consideration to paving motor pools, vehicle parking and maintenance areas, service station areas, AGE areas, small aircraft parking aprons, etc., with RCC so that the Air Force can gain experience with this material and develop a performance history (25:1).

The purpose of this research project is to propose an orderly implementation strategy for this directive. As this is done, the following problem will be addressed:

Problem Statement

How may the U.S. Air Force integrate Roller Compacted Concrete Pavements into its methods of pavement construction and maintenance?

Background

Three paving methods form the basis upon which RCCP technology has been established. They are Portland Cement Concrete (PCC), asphalt cement concrete (ACC), and cement-treated bases (CTB). The oldest of these three is PCC.

As a construction material, concrete has been around for a long time. One of the earliest known uses of concrete was for the burial sepulchre in the Great Pyramid of Egypt (7:25). There, the builders mixed natural lime with varying

sizes of rock rubble to produce a durable and strong wall structure.

The first use of a cement-based paving structure probably originated with the Romans. During their tenure, they constructed over 372 great roads, totaling in length 52,964 miles (7:148). The Romans used a paving procedure much the same as is used today. "The materials used by the Romans for road-making were of two kinds; the stones which formed the mass, and the cement which united them" (7:150). The durability of these roads is legendary, with many miles still in servicable condition.

Concrete continued in use through the middle ages. An interesting use of concrete was on the Highland Roads of Scotland. Cresy (1880) describes these roads:

> Every necessary precaution was taken to render these roads efficient, and where foundations were of a soft nature, concrete was spread entirely over the surface, made with hard stone, or gravel mixed with lime in the proportion of one of the latter to four of the former...for it is very important that there should be a junction between the two bodies, otherwise the stones would be in constant motion, and never form a durable crust; by laying the courses of broken stones on at intervals, the roadway is rendered perfectly solid, and in one mass from bottom to top (7:528).

As technology matured through the Industrial Revolution, the use of cast-in-place concrete as a paving material continued to advance. The use of mechanical equipment for mixing and placement allowed greater and more varied applications. The science of materials also advanced and helped provide more reliable cements. As concrete

paving technology continues to mature, more and more advanced applications are being found for this versatile material. Similar in concept to PCC are cement-treated bases (CTB).

Cement-treated bases have also been around for a while. Early builders found that lime, spread and worked into the soil, provided a much stronger and more durable surface. Today a cement-treated base is often used as an inexpensive means to improve the strength of a soil. In addition to PCC and CTB, one final discovery also helped provide the background for RCCP.

Petroleum began to find widespread use in the 19th century. The heavy waste products of petroleum refinement began to find application as a treatment for road surfaces. This use of asphalt cement rapidly advanced to the mixture and application of asphalt cement concretes (ACC) for pavement surfaces. Due to low cost and ease of placement in comparison to concrete, asphalt soon outdistanced its older relative as the pavement of choice in most applications. The simple means of ACC placement was to be adopted for RCCP use.

Taken together, these three technologies; PCC, CTB, and ACC, form the foundation upon which RCCP has matured.

Scope and Limitations

This research project will provide a summary of the state-of-the-art of Roller Compacted Concrete Pavement. It will also provide a synopsis of recent RCCP experience.

Finally, it will provide a recommended plan for implementation. This project will not attempt to add to the current state-of-the-art from a technical standpoint.

Research Objectives

This research has five objectives. Each addresses a facet of the Problem Statement. The Research Objectives are:

1. To determine the advantages and disadvantages of RCCP.

2. To determine the present knowledge level of USAF Pavement Engineers with respect to RCCP.

3. To establish required characteristics of various types of USAF pavements.

4. To provide a decision support model to help engineers determine when and if RCCP would be a viable design alternative.

5. To provide an implementation schedule that will permit USAF development of RCCP paving technology.

In the next chapter, the literature will provide the background necessary to address these Research Objectives.

II. Literature Review

Overview

Authors take two general approaches to the subject of Roller Compacted Concrete Pavement. First is the functional approach. Many authors have organized their research and reporting according to the major functions involved in the design and construction of RCCP. Others have preferred to approach the subject on a case study basis. This report will include both approaches.

This Literature Review will include four sections. The first section will establish a definition of RCCP.

The second section will cover the various functions involved in design and construction. These areas range from materials selection to quality control and cost.

The third section will highlight six case studies of recent RCCP projects. These projects reflect the progress of the RCCP state-of-the-art.

The fourth and final section will be a summary of literature on USAF paving requirements for aircraft and vehicles. But before any detailed discussion, a definition of RCCP is required.

Definition of RCCP

Over the years, many different terms have been used for Roller Compacted Concrete Pavement. These have included "Rollcrete", "Rollercrete", and "Econcrete". One engineer's

definition of RCCP was "cement spread in layers and steam-rolled (21)."

The definiton used by Dave Pittman of the Waterways Experiment Station will be used in this report.

> Roller-compacted concrete pavement (RCCP) is the product of a relatively new concrete paving technology in which a zero-slump portland cement concrete mixture is spread with modified asphalt pavers and compacted with vibratory and rubber-tired rollers (36:1).

With this definition in mind, the functional aspects of RCCP can now be reviewed.

Functional Review

This section of the Literature Review includes a summary of the information from the following areas; materials, mix design, thickness design, placement, curing, quality control, and cost. Each area has aspects unique to RCCP when compared to other paving methods. The first area of interest is the selection of materials.

Materials. As a building material, concrete has been around for a long time. In 1880, Cresy wrote:

> Concrete is of very ancient use, and formed the foundations as well as hearting of the walls in the remotest ages, and among all nations: it is made of mixing lime, coarse gravel and sand together, with a moderate amount of water (7:724).

In this very early writing, the four constituents of concrete are mentioned. They are coarse aggregate, fine aggregate, cement, and water. These same constituents are

used in RCCP, but a few notes are in order. Of first priority are the aggregates, both coarse and fine.

Coarse Aggregate. Coarse aggregate is the primary structural component of concrete. It can either be naturally occuring (gravel) or processed (crushed stone).

The quality of the coarse aggregate is very important. According to Pittman:

> One of the most important factors in determining the quality and economy of concrete is the selection of a suitable aggregate source. This is as true for RCCP as for conventional concrete (35:3).

Aggregates are chosen on the basis of several criteria. Among these are size, shape, angularity, hardness, cleaness, plasticity, and durability. There is agreement that one of the potential strong points for RCCP is its robustness to less than optimum values for these parameters when compared to PCC. According to Pittman and Ragan:

> Although the quality of coarse aggregate used by the Corps of Engineers to date in RCCP has generally complied with ASTM C 33, satisfactory RCC may be produced with coarse aggregate not meeting these requirements. Local state highway department coarse aggregate grading limits, for example, should be acceptable (35:3).

An asphalt (crushed) aggregate was found to work well on the Portland International Airport (PIA) aircraft parking apron. The designers found that this aggregate produced less segregation, higher flexural strength, tighter surface texture, and a larger number of available producers (1:12,13). The ability to use this type of aggregate

deletes the requirement to remove the deleterious fines by washing the material. This results in substantially lower costs.

Most authors agree that a maximum size coarse aggregate is 3/4 inch (35:3), (1:6), (53:7). Larger size aggregates tend to increase the possibility of mix segregation during transportation and placement.

Fine Aggregate. The purpose of fine aggregate is to fill the voids between the individual large aggregates. The quality of fine aggregate is determined in large measure by its plasticity, or ability to absorb deformation. Research in Australia suggests that lower plasticity (3<PI<7) improves the properties of RCCP (29:9). Some silt has also been found to be benefical, but clays are to be avoided (35:3).

Another vital constituent of RCCP is the cement.

Cement. Cement is the glue that holds the concrete matrix together. Pozzalans (natural cements) and fly ash (residue from coal burning) also have cementitious properties. They have been used in RCCP mixtures to reduce costs and to provide additional fines. The Corps of Engineers suggests the presence of these additives may aid in providing a good surface texture (23:1-2).

Type I (standard) Portland Cement is used in the majority of PCC applications. Research points to the possibility of using Type IV (low heat) in RCCP to allow more time for finishing. However, this benefit results in

lower strength gain which may be a detriment if early pavement use is required (29:9).

Now that the basic constituents of RCCP have been addressed, the combination of these materials into a paving mixture may be discussed.

Mix Design. The concept of adjusting the proportions of the materials in a concrete mixture in order to optimize its properties has been practiced for a long time. Cresy writes:

> Neither gravel nor sand alone will form a perfect concrete, for when large pebbles are mixed with quicklime and water, they are not in any way held or cemented together, but when fine sand is used in the ordinary proportions of common mortar a concrete is formed...(7:724).

As mentioned in Chapter 1 of this report, RCCP was developed on the technologies of three earlier paving methods. This "triad" concept is graphically represented in Figure 1.

As illustrated, the mix design of an RCCP mixture is similar to the design of a cement-treated base, sometimes referred to as soil cement. In this section, the concept of mix design will be reviewed by looking at several design components. These are aggregate gradation, water content, cement content, admixtures, and frost considerations.

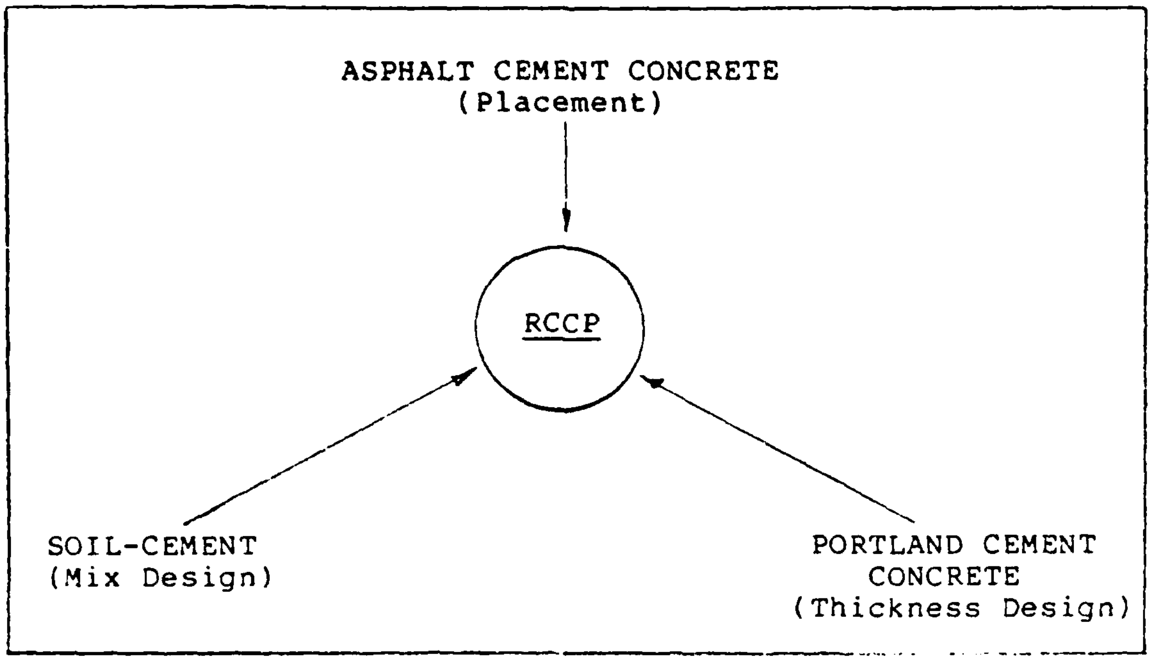

Figure 1. Conceptual Basis of RCCP

Aggregate Gradation. As Cresy states above, a strong mixture is formed when "large pebbles" are combined with fine sand. The proper proportioning of coarse and fine aggregate is a key concern in RCCP mix design. Proportions are determined in two ways. The first method is to use gradation limits. A range is generally specified using sieve analysis. Table I shows RCCP gradation limits recommended by the Corps of Engineers. The concept is illustrated graphically in Figure 2.

TABLE I

Corps of Engineers Recommended Gradation Limits (28:19)

Sieve Size	Cumulative Percent Passing By Weight
1-inch	100
3/4-inch	94-100
3/8-inch	50-74
No. 4	33-54
No. 8	26-47
No. 16	16-39
No. 30	8-28
No. 50	4-15
No. 100	2-7
No. 200	0-5

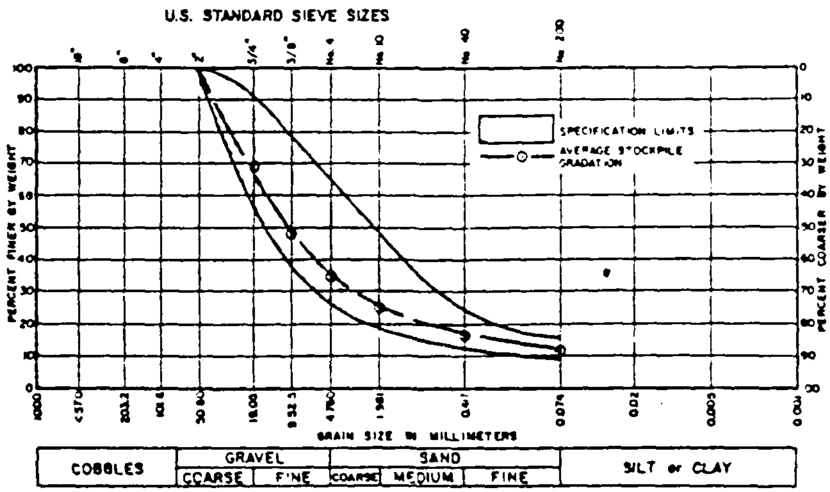

Figure 2. RCC Aggregate Grain Size Distribution (47:51)

Aggregate can also be proportioned on the basis of total weight per unit volume. The final mix design used on the PIA project illustrates this method and is shown in Table II:

TABLE II

Portland Airport Mix Design (1:15)

Material	Weight (lbs/cy)
Cement (Type I)	488
Pozzolan (Centralia Type F)	119
Water	260
Aggregate	3250
	4117

Using both of these methods, the proper gradation and the proper volume of aggregates are provided.

The next aspect of RCCP mix design is the use of water.

Water. As shown in Figure 1, RCCP mix design was developed from soil-cement technology. In soil-cement design, the amount of water used is generally determined by the requirement to lubricate the compaction process rather than to hydrate the cement (33:36), (32:6). Reeves and Yates explain:

Note that in soil compaction theory the function of water in a granular mix is to lubricate the mix so that a higher dry density can be achieved with a given compactive effort. That is, contrary to concrete theory, additional water above cement hydration needs may be required up to the optimum point for a greater dry density and the corresponding greater cured strength (47:50).

The concept of density vs. moisture content is illustrated in Figure 3. This figure shows that the density of an aggregate mix increases with increasing moisture, but only up to a point. However, as moisture is added past the optimum moisture content, density begins to decline.

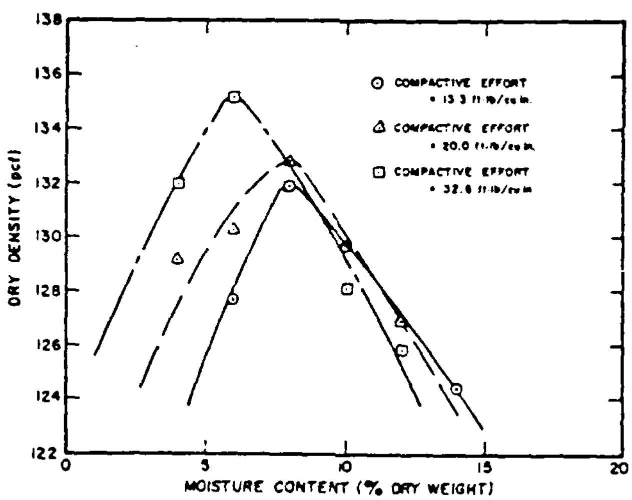

Figure 3. Dry Density vs. Moisture Content (47:53)

A final point concerning water content is the need to make on-site adjustments to water amount. The quantity of water used depends on such variables as temperature, wind, relative humidity, and compaction. The Corps of Engineers Engineering Technical Letter on RCCP states:

> The total water content of the mix shall be controlled by the Contractor at the amount directed by the Contracting Officer's representative... In general, it is expected that the total water content will be within the range of .... to .... percentage points below laboratory optimum...(28:21).

The key concept is that the design water content is just a recommendation. The field crew must continuously adjust the water quantity based on actual conditions.

A third and perhaps the most critical aspect of mix design is cement content.

Cement Content. The determination of the amount of cement in an RCCP mix is approached in two ways: water-cement ratio and total weight of cement per unit volume.

The water-cement ratio is the proportion by weight of water to cement when the concrete is first mixed. Using the information from the PIA project in Table 2 above, the water-cement ratio would be:

$$\frac{260}{488 + 119} = 0.43$$

According to Dynapac, an industry leader in RCCP, this ratio is very important (2:11). Piggot concurs, "The strength of an RCC mixture is controlled primarily by the water cement ratio and the degree of compaction attained (35:6)."

The relationship between the amount of water, cement, and means of placement is illustrated quite well in a piece of Swedish literature (Figure 4):

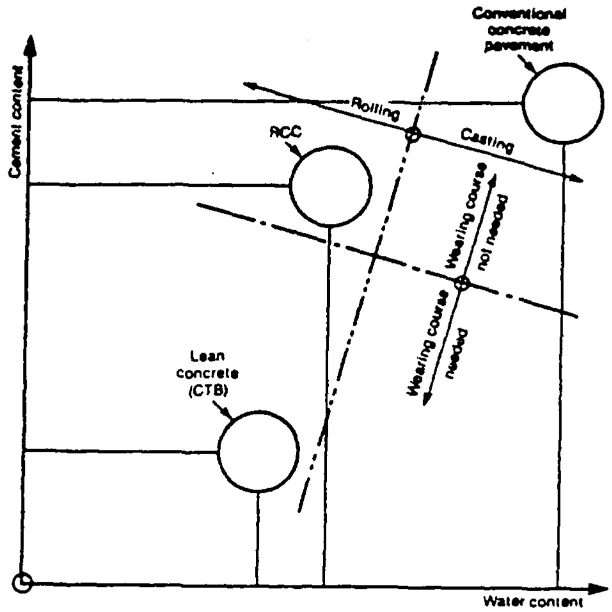

Figure 4. Comparison of RCCP, PCC, and CTB (2:10)

The second criteria for determination of cement content is the total percent by weight. Once again using PIA information, this percent would be:

$$\frac{488}{488 + 119 + 260 + 3250} = 11.9\%$$

This amount is within the tolerances specified by the Corps of Engineers (28:20). It is also near the range generally used on the pioneering RCCP projects in Canada (26:11).

Another aspect of RCCP mix design is the use of admixtures.

Admixtures. Admixtures are materials added to a concrete mix to improve its properties. Pozzolan is the

only admixture found so far to be of benefit to RCCP. As mentioned earlier, pozzolans are residues from coal burning. In mix design, pozzolans can take the place of some of the cement, thereby decreasing cost and improving workability (2:11).

Another admixture commonly found in standard PCC is an air entrainment agent. These are generally added to increase frost resistance. Most authors agree that air entraining agents should not be included in RCCP. This is due to the small amount of cement paste in the mixture (26:13), (2:11). Canadian projects without air entrainment are performing well (32:6).

This discussion of air entrainment leads next to the subject of frost resistance.

Frost Resistance. All concrete is permeable to some degree. The degree to which a pavement can resist repeated freeze-thaw cycles is dependent on the system of air voids inside the concrete, and the way in which this system carries water. A formal evaluation of the ability of RCCP to resist this freeze-thaw action was carried out by the Corps of Engineers. Their findings indicate that RCCP offers better than expected frost resistance. This could be due to the "cohesiveness of the mixture, pug-mill mixing, and the method of compaction (44:2)." As mentioned above, Canada has had good frost resistant performance from their RCC pavements (2:11).

Having examined mix design of RCCP, the next subject will be the determination of pavement thickness.

Thickness Design. The question of pavement thickness has been considered for many years. In discussing the specifications of the Highland Road in Scotland, Cresy writes:

> The depth of the bed of concrete varied according to circumstance: in some instances, 6 inches was found sufficient, in others more than double that depth was required...(7:528)

Today, five criteria are used to determine pavement thickness. These are the magnitude of load, frequency of load, load contact area, subgrade strength, and pavement flexural strength (8:5), (26:9), (33:35). Much of modern pavement design theory is built on the work of Westergaard (54:240). Two key issues in thickness design are the determination of flexural strength, and the thickness design process.

Flexural Strength. Westergaard established that a concrete pavement acts essentially as a beam supported only minimally by the subgrade. Therefore, the strength of the pavement comes primarily from the flexural strength of the concrete. This is in contrast to a flexible pavement which derives its strength entirely from its support structure.

Using this concept, RCCP may be a more efficient pavement structure than standard PCC. This is due to RCCP's

intrinsically higher flexural strength in comparison to standard PCC. White writes:

> In pavement design the flexural strength is a significant factor (1). Laboratory flexural strength tests of pavement samples indicate RCCP can develop a twenty-five percent higher flexural strength than a conventional concrete pavement. In large part, this higher flexural strength will come from a higher density achieved from the compaction applied during construction (53:16).

There is agreement with White that RCCP can develop a significantly higher flexural strength than its PCC counterpart (8:6), (35:7). However, some disagreement is apparent as to how to treat this increase in strength.

Delony indicates that designers should use the higher strengths of RCCP (8:6). Piggott cautions that due to the inherent inaccuracies of RCCP mixing, a reduction coefficient of 10 to 15 percent should be considered (32:4). The Corps of Engineers recommends that no increase or decrease be incorporated. They advise that until more construction history becomes available, RCCP thicknesses should be based on the same calculations as standard PCC (35:7).

Once a design flexural strength has been selected, the process of thickness design can begin.

Thickness Design Process. Slightly different thickness design methods are used by the Portland Cement Association, the Federal Aviation Agency, and others. The U.S. Air Force employs a graphical method which uses the five criteria stated earlier. An example of this design

method is shown in Figure 5. The designer enters the graph on the left at the chosen flexural strength, moves right to the subgrade modulus, down (or up) to the traffic area and right to pavement thickness.

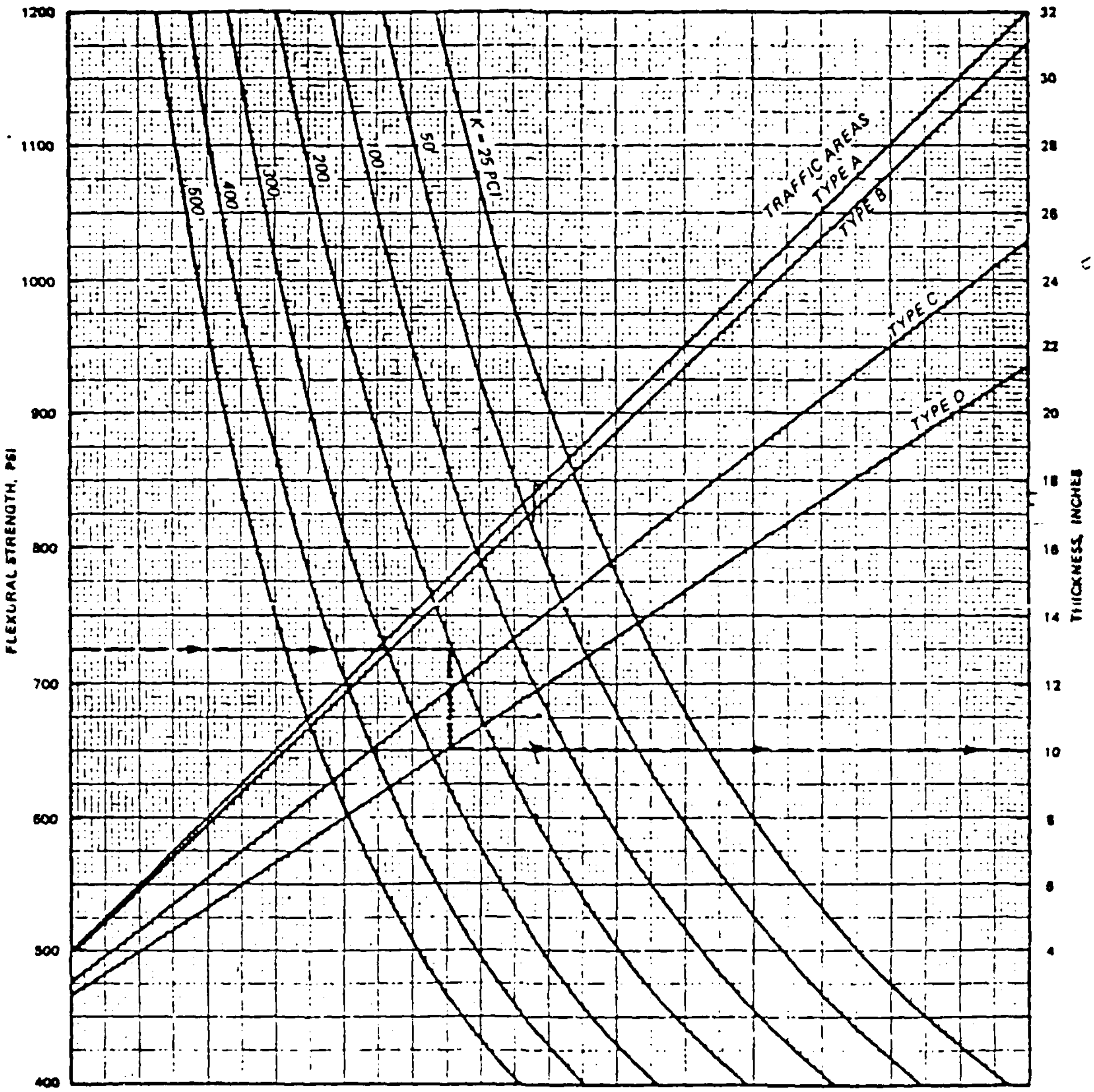

Figure 5. USAF Pavement Design Curve (16)

An interesting comparison of three different design methods was done by White (53:18-20). He compared design thicknesses using the American Association of State Highway and Transportation Officials, U.S. Army/Air Force, and the Portland Cement Association design methods.

White chose a storage area subject to a forklift single-axle load of 40,000 pounds. The only variable in the calculations was flexural strength. Based on recent construction experience, he used a flexural strength of 750 psi for the RCCP while using 600 psi for the conventional concrete. He found an approximate thickness reduction of one inch. His results are shown in Tables III-VI.

TABLE III

Thickness Using AASHTO Method

	M_R (psi)	Working Stress (psi)	E (psi)	Traffic	k (pci)	Thickness (inch)
Conventional Concrete	600	457	4.2×10^6	8.4×10^6	300	9.5
RCC	750	564	4.2×10^6	8.4×10^6	300	8.5

TABLE IV

Thickness Using COE/AF Method for Storage Areas

	M_R (psi)	Traffic (veh/day)	Traffic Category	Design Index	k (pci)	Thickness (inch)
Conventional Concrete	600	100	VII	10	300	9.7
RCC	750	100	VII	10	300	8.3

TABLE V

Thickness Using PCA Method for Industrial Floors

	M_R (psi)	F.S.	Working Stress (psi)	Stress per 1000 lb	Thickness (inch)
Conventional Concrete	600	2.0	300	7.5	9.0
RCC	750	2.0	375	9.4	7.8

TABLE VI

Thickness Using PCA Method for Highways

	M_R (psi)	Thickness (inch)	Stress Ratio	Allowable Repetions	Erosion Factor
Conventional Concrete	600	9.5	0.245	340,000	2.36
RCC	750	8.5	0.227	1,700,000	2.48

Having investigated mix design and thickness design of RCCP, the next subject is the third leg of the conceptual triad, the actual placement of the pavement.

Placement. The placement of concrete has changed greatly since 1880:

> Whenever concrete is used for the foundation of a building, it should be thrown from as great a height as possible, which compresses it into a more solid mass: its depth when laid in trenches, or spread over an entire surface, should never be less than 4 or 5 feet, and where great weights are to be borne not less than 6 feet (7:724).

Although the methods of concrete placement have changed, the desired result is the same for both RCCP and PCC - a well compacted uniform matrix of coarse aggregate, fine aggregate, and cement.

This section reviews the major aspects of RCCP placement as covered in the literature. However, it does not cover these subjects in detail. The definitive work at that level of detail is Pittman's Construction of Roller-Compacted Concrete Pavements (35).

The major areas of the placement process covered here are the working surface, test section, mixing, laydown, compaction, cracks, joints, and curing. A review of each of these areas follows.

Working Surface. As explained earlier, a concrete pavement is designed as a beam to support nearly the entire design load. As such, the condition of the subgrade and/or base course is of only minimal concern. Naturally, a slightly stronger subgrade will result in a slightly thinner

pavement. However, the concept of using a poor subgrade must be modified when using RCCP. White explains that vibratory compaction on a weak foundation can result in three problems: additional cracks, low compaction densities, and "pushing" of RCCP aggregate into the subgrade (51:18). Other authors point to the need for a working surface to provide uniform grade (8:8) and drainage against frost action (36:3), (32:8).

Test Section. Most asphalt or concrete pavement contracts call for the contractor to complete a test section prior to commencing the actual work. The Corps of Engineers has insisted on this practice for RCCP projects (35:8), (36:3), (28:21). Pittman says:

> Construction of a test section allows the contractor to demonstrate his ability to mix, haul, place, compact, and cure RCCP before the major construction takes place. The test section is usually constructed at least one month prior to the start of the major construction, so that samples for strength may be taken directly from the test section (36:4).

The test section provides at least two additional benefits. First, it allows the contractor to practice both fresh and cold joints, and second, it allows for calibration of the nuclear density meter (35:8).

Mixing. There is agreement that the constituents of RCCP should be mixed in a twin-shaft pugmill mixer similar to that used in asphalt batching (52:7), (29:11), (1:16). A mobile pugmill plant has been used in some cases (29:11).

The pugmill allows a vigorous mixing of the small amount of water (36:5). The recommended capacity of the plant varies from 250 to 600 tons/hour (36:5), (1:16), but it must not be greater than the ability of the placement and rolling equipment (36:5).

Once properly mixed, the RCCP is placed into dump trucks for transport to the site. A maximum haul time of 15 minutes is recommended (36:5).

Laydown. As previously mentioned, the RCCP laydown process is quite similar to an asphalt paving project. The dump trucks deliver the mix directly into the paving machine hopper. The paving machine then screeds the mix onto the subgrade.

Opinions vary as to the exact characteristics desirable in the paving machine. A track-mounted machine was preferred over rubber-tired for better mobility (3:3). When using a standard paving machine, a vibratory screed provided good initial compaction (8:8), (36:6), (35:10). On the PIA project, a paving machine built by ABG of West Germany used screed-following tamping bars to provide high (98%) initial compaction prior to rolling (1:16).

Several authors recommend a maximum lift thickness of 8 to 10 inches, although this depends on the capability of the paving machine (52:7), (32:8). Automatic grade control devices (i.e. stringline or "ski") are recommeded (34:6), (28:14).

Compaction. A ten-ton, dual-drum, steel wheel vibratory roller is recommended for initial consolidation (36:6), (29:15). The rolling pattern for RCCP is critical (36:7-9).

Once initial compaction is accomplished, some authors recommend several passes with a rubber-tired, non-vibratory roller to close the surface texture (36:7), (29:15), (35:13). A final non-vibratory steel wheel rolling may be helpful to remove any roller marks (35:13).

Cracks. Concrete shrinks as it cures. RCCP will develop cracks because it is placed without shrinkage reinforcing steel. Most RCCP projects have been allowed to crack at random without deleterious effects (32:9). The Corps of Engineers have experimented with sawing contraction joints on two projects. Spalling and random cracking convinced them to abandon these efforts (35:14). However, White believes saw cutting of contraction joints to be a viable solution (53:14).

Joints. Another placement consideration is treatment of joints. A joint is placed where a paving lane is deliberately ended. It occurs either at the end of a days paving (transverse) or along the edge of a paving lane (longitudinal).

There are two types of joints, fresh and cold. A cold joint occurs when two sections of pavement cannot be consolidated together (36:9). Timing of consolidation is critical due to the small amount of water in RCCP. A cold

joint occurs 90 minutes after placement (36:10). Once a joint is considered cold, it must be cut back to a vertical face and wetted prior to an adjacent area being placed (32:9).

Curing. Once placement and compaction are complete, curing takes place. Piggott explains:

> Since the water content in the mix is established on the basis of optimum moisture content for the maximum density and not water/cement ratio, there is practically no free water available as a reserve for curing. Therefore water from an extenal source is vital to strength gain in the first days after placement (32:10).

A combination of continuous moist curing and membrane curing is recommended (36:11), (53:14). Wet burlap, water spray and wet sand are options for initial curing (53:15). Membranes are allowable after the first 24 hours (36:12). The PIA project used a water truck with a fog spray nozzle for the initial cure. Later, curing was provided by a sprinkler system (1:17).

Having now reviewed the placement of RCCP, the next subject will be quality control.

Quality Control. Quality Control (QC) is the process of assuring that materials and finished product conform to the contract specifications. Various QC tests are essential to insure a quality product. These tests cover materials, plant calibration, in-place density, moisture content, cement content, smoothness, concrete strength, and thickness (36:13), (27:5). Each of these is reviewed below.

Materials. The requirements for RCCP materials have already been discussed. The tests to insure adherence to these requirements include a variety of ASTM tests for such attributes as hardness, soundness, and shape. These tests are similar for PCC and RCCP.

Plant Calibration. A key to quality concrete is a well-calibrated mixing plant. It is here that the materials are proportioned and mixed. According to Pittman:

> Gradation tests should normally be performed on the combined aggregates three times per day: in the morning, at midday, and in the afternoon. The samples should be taken from the conveyor before the cement or fly ash is added to the combined aggregates. The calibration of the plant should be checked each day before production begins (36:13).

In-place Density. One of the key advantages to RCCP over standard concrete is its high density. However, as late as 1984, no standard method existed to measure in-place density (3:4). More recently, the nuclear moisture/density meter has come into general acceptance as a means to measure both moisture and density (1:20). Calibration of the nuclear meter has been of some concern. Abrams and the team on the Portland Airport project solved the problem by constructing a large ultra-dense concrete block from the pavement mix. This became the 100% standard for daily calibration of the nuclear meter (1:20).

Moisture Content. As explained above, the nuclear meter is also used to measure in-place moisture. The immediate feedback of the test is necessary to allow the

plant operator to fine-tune the mix for optimum laydown and compaction.

<u>Cement Content</u>. The measurement of cement content is especially important because RCCP uses less cement per unit volume than standard concrete. Cement content measurement is generally a laboratory test and does not afford on-site feedback. The literature reveals two interesting ways around this problem.

The Corps of Engineers have developed an experimental Concrete Qualtiy Monitor (CE CQM) that measures cement content by dissolution in a dilute nitric acid. Cement content is determined proportional to the resulting calcium content (27:5). Another on-site cement content test is used in Australia. It measures heat rise when concrete is added to a solution of sodium acetate and acetic acid (29:17).

<u>Smoothness</u>. RCCP is measured for smoothness in the same manner as PCC. The parameter generally given is the maximum allowable deviation in any given ten foot section. The Corps of Engineers Guide Specification sets this parameter at 3/8 inch (28:9). The PIA project tightened this to 1/4 inch (1:18). At 1/4 inch in ten feet, surface smoothness conforms to requirements in the Corps of Engineers Guide Specification for aircraft parking aprons (12:3). Another consideration is surface texture. The Corps of Engineers advise that qualified workmen can produce a surface texture similar to that of asphalt concrete pavement (36:15).

Concrete Strength. The two main measures of concrete quality are compressive and flexural strength. Tests are performed in the same way as for PCC. However, gathering the sample is somewhat different as there is not yet a standard ASTM method for core and beam construction. A vibrating table consolidation procedure is recommended by the Corps of Engineers (36:14). In-place tests are obtained by coring and sawing as with standard concrete.

Thickness. A final QC measure is pavement thickness. This is initially controlled by the application thickness of the paving machine. This application thickness can be estimated at 1.25 times the desired final thickness (35:7). The Corps of Engineers Engineering Technical Letter recommends a final thickness tolerance of plus or minus 1/4 inch from design thickness (28:9). The final thickness can be checked when the concrete is cored for strength tests (36:14).

The last functional area to be examined is cost. Although not strictly a functional aspect of RCCP, it is a result of the functional aspects, and is of primary concern to Pavement Engineers and engineering managers.

Cost. The literature varies widely as to potential savings from the use of RCCP. Figures may range from 18% (26:9) to 32% (1:20) below the next lowest alternate bid. Actual savings are more informative and will be covered under the case study section of this chapter.

Although the figures vary, the reasons for the savings are consistent. Summarizing these reasons, the Corps of Engineers state:

> The cost of RCC concrete is less than that of conventionally place concrete. The major savings is due to lack of formwork, less labor, less construction time, and no hand finishing. Higher percentage may be realized with larger projects...(48:9)

Other contributors to cost savings are the ability to use poorer quality aggregates (33:45), no requirement for rebar (45:50), and no requirement for joints (45:50), (26:8).

Abrams and the PIA team note that the cost savings for bid evaluation are based only on first cost. On their project, RCCP was compared with ACC. A life-cycle cost approach would have revealed even more savings (1:20).

The literature offers a mixed prognosis for the future trends of construction costs for RCCP. The Corps of Engineers expect the costs to decrease as more contractors gain experience with RCCP and consequently reduce the amount of contingency in their bids (48:6). Abrams et al expect costs to increase as contractors increase profit margins (1:20).

Having now reviewed the functional aspects of RCCP, the next topic will be the review of several actual RCCP construction projects. This review will synthesize many of the issues raised in the functional section.

Case Studies

This section of the Literature Review provides a representative history of RCCP projects. The objective is to synthesize the indiviual RCCP concepts presented in the functional review portion of the literature review. This section begins with a summary of early Canadian projects. Next are six recent projects from various locations in the United States. (Note: key statistics of each project are located in Table VII at the end of this section.)

Early Projects. As mentioned earlier in this paper, the use of cement-treated materials to construct durable paved surfaces probably began in Roman times. The first recorded use of true RCCP may be at the Yakima Airport, Washington. Placed in 1941 by relatively primitive equipment, the pavement is still in use with only a thin asphalt overlay (24:288).

Most of the early RCCP projects were built in Canada. The turning point in the evolution of RCCP came in 1972 with a 55 acre lumber terminal built in Vancouver, British Colombia (B.C.). This project was in reality a cement-treated base with a thin asphalt concrete cap. However, it used a higher cement content (8%) than normal CTB (33:33). The project was placed with an asphalt paving machine and cost 20 percent less than the asphalt and concrete design alternates (8:1).

Using the good performance record of this project, Canadian engineers decided to construct a pavement without

the asphalt cap. The first project of this type was the 48,000 square yard (SY) Cayuse log sorting yard in Vancouver, B.C., subject to loads of up to 100 tons per axle from the log stackers, this pavement has performed well since its 1976 construction (24:293).

The first test of RCCP in a really severe winter climate came with the construction of the Bullmoose mine project at Tumbler Ridge in inland British Colombia (24:293). Built in 1983, the project included a 24,000 SY coal storage area and 13 miles of haul road. The quick laydown attribute of RCCP was demonstrated by the construction of the coal storage area in only three days (42:2). The asphalt-capped RCCP road is performing well in this severe freeze-thaw area (24:293).

RCCP technology has also been under development in other countries. Norway began to use RCCP on roads as early as 1981. They solved the surface tolerance problem by milling the pavement after placement (2:11). Australia has been using RCCP with aspahlt, crushed rock, and sprayed bituminous surfaces since 1978 (29:2). Sweden has also used RCCP on light load pavement areas (2:11).

In the United States, formal research began in the early seventies. No-slump concrete studies began at the Corps of Engineers Waterways Experiment Station in 1973 (8:4). They built test sections to test the use of marginal materials and compaction characteristics (35:2).

The Corps of Engineers has taken the lead in this country's RCCP research and development. The first test projects took place on several U.S. Army bases. The next section of the Literature Review deals with these and other specific cases.

Fort Stewart, GA. This project consisted of a tank apron access road approximately 200 feet long and 20 feet wide. It was a less than optimum test case from the standpoint that it was built on a poor subgrade. It also used troop labor, a ready mix truck, and it was placed with a grader instead of a paving machine (24:293). Even under these conditions, the results were quite good. An average compressive strength of 5220 psi and flexural strength of approximately 1000 psi were obtained (43:4,5). The users were pleased (24:293).

Some new RCCP concepts were tried during this project. These included dowels, joint sawing, and wet sand cure. The dowels were found to be unnecessary. However, the wet sand cure performed well, and the relatively constant moisture level may have helped prevent ravelling at the sawn joints (53:15).

Fort Hood, TX. The Fort Hood project was a much larger and better controlled experiment. The project consisted of a 500 X 328 foot tank parking apron. It was ten inches thick and unreinforced. Most of the project was built using a 1.5 inch maximum sized aggregate. This led to some segregation and surface texture problems. Reducing the

maximum size to 3/4 inch relieved much of this problem (24:293).

Fort Hood attempted the use of both burlap and compound cure methods. However, the burlap mats were not kept wet and a poor surface resulted (22:3). Sawn joints were again tried on this project. The results were undesirable (22:3).

The expeditious nature and lower cost of RCCP were again demonstrated with a total construction time of 11 days and a cost savings of 15 percent over reinforced concrete (49:16), (36:3). Strength results were favorable with averages of 4830 psi in compression and 834 psi in flexure (22:9).

Fort Lewis, WA. The Corps of Engineers research and development effort continued on the Fort Lewis project. Having heard about the Canadian success with this new material, the Seattle District Corps of Engineers appropriated funds to place a small quantity of RCCP (52:1).

The project consisted of a 700 X 23 foot insert into an existing high-traffic roadway used by both rubber and tracked vehicles. The subgrade preparation was done by military labor (52:2). A contract was awarded to an experienced Canadian firm to place the RCCP (4:6). An average surface tolerance of 3/8 inch in 10 feet was obtained.

The two main issues investigated on this project were mix design and jointing. Two mix designs were used. One was a natural gravel with fly ash while the other used a

crushed 5/8 inch maximum asphalt aggregate mix. Both placed and finished well, but the asphalt mix obtained a 30 percent higher flexural strength than the gravel mix (24:295).

Cold joints were mandated by the contract (4:6). This allowed the Corps to develop some experience for use on future larger projects. As a result, several lists of "lessons learned" were developed. These included not only jointing, but all other phases of manufacture and placement (52:7), (48:3).

Finally, the Fort Lewis project was a turning point for the use of RCCP in the United States. The demonstration was well attended (3:1) and received press from those outside the military community (24:295), (4:6). Following this project, RCCP use in the private sector began to increase. The next three cases deal with some of these private sector projects.

Houston Intermodal Terminal, TX. The first major commercial RCCP project took place at Burlington Northern's railway piggyback loading yard in Houston, Texas. This 54,000 SY area is subject to similar loads as the Canadian log sorting yards. Very heavy (110k per axle) rubber-tired loaders are used to hoist and load containers onto railroad flat cars. The design pavement was 18 inches thick (46:50).

A unique aspect of this project was the placement process. The entire 18 inches of material was placed in a single lift by dump trucks and spread by a laser-controlled dozer (46:51).

Houston was also one of the first projects to allow alternate bids on varying designs. RCCP was low bid of 6 alternates, 4 asphalt and one of conventional concrete (46:50). The average seven day strengths were 3932 psi for core compressive and 539 psi in flexure (39:1).

The Portland Cement Association gave a short course on RCCP during the placement of the Houston project. About 90 people attended (46:51).

Some placement problems occured during the project. Notable was the attempt to use a grader to modify the surface after rolling. The attempt resulted in pullout of some of the aggregate.

Tacoma Intermodal Terminal, WA. The next in the series of RCCP projects also took place in a railroad loading area, this time in Tacoma, Washington. Two areas were paved totaling 94,000 square yards (40:1,2). The same asphalt aggregate as the Fort Lewis project was used (24:295).

According to the designer, the two main issues that drove the decision to allow RCCP as a bid alternate were cost and time (26:7,8). The results of the alternate bid were that RCCP came in 18 percent below the asphalt alternate (24:295), and a 59,000 SY area was placed in 10 days (40:1).

The most important new feature developed at the Tacoma project was the use of a new paving machine. One section of the project was paved using a Titan machine manufactured by ABG of West Germany. The unique feature of this machine is

a dual tamping bar system located just behind the screed. The tamping action provided two benefits. First, the higher initial density required less rolling (26:20), and second, the initial consolidation provided a more accurate surface tolerance (24:297). At Tacoma, an initial density of 94 to 95 percent of the modified Proctor was obtained from the paver alone (24:297).

A Corps of Engineers review of the area after two months of use showed good results, with a surface texture almost identical to asphalt concrete and little surface ravelling. Surface tolerances were good and a drive across the pavement at 50 mph was only slightly bumpy (34:1).

Portland International Airport, OR. The final project considered in this section of the Literature Review is the 41,000 SY aircraft parking apron at the Portland International Airport, Oregon. As well as being the first RCCP structure for aircraft use built in the United States, it was a good synthesis of all the RCCP technology available to date.

The project was required due to an upgrade of the airport's navigational aids facilities. The upgrade forced a relocation of the airport's transient aircraft parking apron (1:4). The controlling aircraft in the design process was the 155,000 pound Boeing 727. The pavement was designed to a thickness of 14 inches using FAA criteria (45:20). The owners and the designers had heard of RCCP projects in Canada and at Fort Lewis. The main advantages of RCCP for

an airport pavement were summarized by the Portland Cement Association as (41:5):

1. Resistance to chemical attack from hydraulic oil and fuel
2. Long-term durability and low maintenance costs
3. Negligibile rutting or creep problems under heavy and long-term loading
4. Lower placement costs

After studying the issues, the decision was made to allow RCCP as an alternate bid item to ACC (1:4).

The designers saw at least five challenges as they prepared the documents for the RCCP option. These were surface tolerance, smoothness, joint control, density, and contractor availability (1:2,6).

The surface elevation tolerance specified in the contract was plus or minus 3/8 inch from grade. The smoothness criteria was 1/4 inch in 10 feet. To meet this criteria, the designers specified electronic grade control. In addition, the contractor took advantage of the experience on the Tacoma project and used a German ABG paving machine with a vibratory screed and precompaction tamping bars (1:16).

Joint control was handled by specifying a maximum of 60 minutes between placement of the two 7 inch lifts. This eliminated cold horizontal joints. Fresh vertical joints were cut to near vertical before the adjacent section was placed (1:18).

Density was determined by comparison of placement densities with a very dense test block constructed during the mix design stage. This was a piece of trailblazing work as there are no accepted standards for calibration of nuclear denseometers on RCCP projects (1:19).

During design option evaluation, a survey of area contractors revealed a receptivity to RCCP (1:6). The bids revealed RCCP to be 32 percent less costly than the asphalt concrete alternate (1:2) with an in-place unit cost of $40.73/CY (24:297). The winning bid ($687,370.65) was less than half (49%) of the engineer's estimate ($1,397,391.95) (1:21), (6:8).

TABLE VII

Case Study Summary

Project Name	Description	Yr	Area	In	$/CY	%	Dur	Comp	Flex
Fraser River, Vancouver, BC	Log Loaders (100T/axle)	76	36000	15					
Cayuse Camp, Vancoucer, BC	Log Loaders (100T/axle)	76	48000	14	21	22		4210	
Port McNeil, Vancouver, BC	Log Loaders (50T/axle)	79	29000	12					
Bullmoose Mine, BC	Coal Loaders (70T/axle)	83	24000	9			3		450
Ft. Stewart, GA	Tanks (30 T)	83	600	10				5220	1000
Ft. Hood, TX	Tank Apron (30T)	84	20000	10	58	15	11	4830	834
Ft. Lewis, WA	Track & Tire Veh	84	1800	8.5	95		2	6100	600
Houston, TX	Rail Loaders (54T/axle)	85	54000	18	54	20	90	3932	539
Tacoma, WA	Rail Loaders (54T/axle)	85	94000	17	43	18	10	5220	750
Portland, OR	Aircraft Pkng (75T)	85	41000	14	41	32			710

KEY TO CATEGORIES

Yr	=	Year Constructed (Note: projects are in chronological order)
Area	=	Surface Area in Square Yards
In	=	Thickness in Inches
$/CY	=	In-place Cost in Dollars per Cubic Yard
%	=	Percent Below Alternate Bid
Dur	=	Construction Duration in Days
Comp	=	Compressive Strength in Pounds per Square Inch
Flex	=	Flexural Strength in Pounds per Square Inch

Having now looked both at functional considerations and case studies, the final section of the Literature Review will be a summary of USAF literature pertinent to the use of RCCP.

USAF Literature

Many USAF publications cover information that concern the possible use of RCCP as a paving material. The following exerpts summarize that information. Three source categories will be covered: regulations, manuals,and correspondence. A design engineer considering the use of RCCP is encouraged to investigate each source in detail.

Regulations. AFR 88-15 sets the tone for potential use of RCCP in the section on "Need for Economy":

> A primary objective in military construction is to provide facilities with low construction costs and low maintenance costs consistent with the anticipated duration of the military requirement. Selections of materials and components should be made from a minimum range of functionally practical sizes and types of construction components (11:1-3).

After establishing a general doctrine of economy, AFR 88-15 states which pavement areas must use rigid pavement (11:2-4). The reader should bear in mind the advantages and disadvantages of RCCP when reviewing the following list of mandatory rigid pavement areas:

1. Aircraft parking, service, and preflight ramps
2. Runway ends (1000 ft.)
3. Primary taxiways

4. Dangerous cargo, power check warmup, arm/disarm, holding, and washrack pads

5. Helicopter parking, maintenance, and service ramps

6. Any other area subject to jet blast or fuel damage

7. Liquid oxygen storage areas (to eliminate joints)

Manuals. Moving from regulations to manuals, AFM 85-8 Chapter 4 provides "...guidance for effective maintenance...(13:1-1)" of surfaced areas.

AFM 86-2 establishes "...type, number, and size...(14:i)" of USAF facilities. While not bearing directly on the choice of pavement materials, this manual provides criteria for sizing of pavements.

AFM 88-6 Chapter 1 provides "...general concepts and an outline of the design analysis for the design of airfield pavements and drainage (15:1)." Several important issues concerning possible use of RCCP are brought out in this manual. Perhaps most important is the design analysis procedures presented in Appendix A (15:A-1). This section establishes such issues as availability of construction materials and recommended design methodology.

Chapter 3 of AFM 88-6 presents "...procedures for design of rigid pavements...(16:2)." Chapter 4 of AFM 88-6 presents the "...criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action (17:1-1)." Chapter 8 of AFM 88-6 provides general guidance for "...preparation of contract specifications and construction

of concrete pavements...(18:5)." One key aspect of this chapter is the surface smoothness requirements (18:33). Roads are governed by a maximum deviation of 1/8 inch in 10 feet, effectively placing them outside the constructable tolerance of RCCP. However, parking and storage areas are limited to 1/4 inch in 10 feet, the same specification as was used on the Portland Airport project.

AFM 88-7 presents criteria for roads, streets, walks, and open storage areas. Chapter 1 provides design criteria (19:3), and Chapter 5 provides geometric data (20:2).

A final source of USAF literature is correspondence.

Correspondence. Colonel Klingensmith's 22 Apr 1985 letter (25) recommending that MAJCOM's begin use of RCCP was mentioned in Chapter 1.

The Engineering and Services Center followed up that letter with a recommendation that MAJCOM's attend a Portland Cement Association short course of RCCP at the Portland Airport (51:1). In that letter, they also transmitted a copy of the the Corps of Engineer's guide specification for RCCP (12). This guide specification was updated and is in draft form at the present time.

Literature Summary

Although RCCP is a young technology, a good deal has been written about it. This review began by defining Roller Compacted Concrete Pavement as a dry, lean concrete placed with asphalt paving equipment. It then covered a functional approach looking at such issues as mix design, placement,

and quality control. Next, a case study approach traced the evolution of RCCP technology from its Canadian infancy to the Portland International Airport project. Finally, a summary of pertinent USAF literature put RCCP in an Air Force perspective.

Next to be presented will be a methodology to achieve the Research Objectives and respond to the Problem Statement.

III. Methodology

Overview

This chapter presents the method by which the Problem Statement and Research Objectives will be addressed.

Paraphrased, the Problem Statement is, "There is a new way of placing concrete, so what should the Air Force do about it?" The five Research Objectives that respond to this question range from a very general summary of the characteristics of RCCP to a very specific implementation schedule.

The Research Objectives will form the outline for this chapter. Each response will be built on the results of the previous objective. Taken together, these objectives will answer the overall problem stated above.

Using this logic, the first objective is to establish the advantages and disadvantages of RCCP.

Research Objective 1: Advantages and Disadvantages of RCCP

The tool to establish this information is the Literature Review (Chapter 2). Chapter 2 presented past experience with RCCP. The information found in the literature will be consolidated into a summary of the strong and weak characteristics of RCCP. This summary will serve as the basis for the decision support model to be discussed under Research Objective 4.

This information established the technical basis. The next objective begins the transition from general experience to specific experience within the USAF.

Research Objective 2: Present Knowledge Level

Background. Each base has someone who is responsible for pavements. This individual is generally a civil engineer in the Design Section of the Base Civil Engineering squadron. The overall problem statement asks how RCCP may be integrated into the USAF paving program. At the base level, it will be the Pavement Engineer who will ultimately implement an RCCP project. Therefore, it is necessary that the general background knowledge of USAF Pavement Engineers be established.

Survey. The tool to establish this information will be a survey of engineers attending the Pavements Engineering course at the AFIT School of Civil Engineering, Wright Patterson AFB, OH. The students attending this course represent a cross-section of both base and MAJCOM level engineers. The objective of this survey will be to determine how familiar the average Pavements Engineer is with the concept of RCCP. The reader should note that the relatively small number of respondents to this and the following survey will not allow statistical significance. Therefore, complete generalization across the entire Base Civil Engineering career field is not practical. However, trends will become apparent and will aid in further research development.

The survey will be divided into two main parts. The first part will establish the demographics of the group. Questions concerning base location, grade, and years of pavement experience will determine this information.

The second part of the survey will establish specific experience with RCCP. In this part, the questions will deal with level of familiarity and perceived technical competence. A final question will deal with their knowledge of current USAF policy concerning RCCP development. A copy of the background survey is in Appendix A.

Analysis. A frequency of response analysis will be used on each question of the survey. These results will indicate the familiarity of USAF Pavement Engineers with RCCP. They will also give some indication as to how much additional familiarization will be required before RCCP construction can be carried out on a regular basis.

These first two objectives establish a background for the specific evaluation of RCCP for USAF use. The next objective brings USAF uses into clearer focus.

Research Objective 3: USAF Pavement Characteristics

Background. The USAF owns and operates many different types of pavements. These range from aircraft runways to vehicle storage areas. Each pavement has its own set of required characteristics. The airfield for example may require a very smooth surface with a high quality surface texture. The vehicle storage lot on the other hand may require less smoothness but more strength. In order to

properly determine how RCCP might meet USAF needs, these required characteristics must be established.

Category Codes. The USAF categorizes all real property with a six-digit category code. An example of this code is 111111 for the runway. Each specific category of real property has its own code. There are 35 different categories that deal with pavements. In order to simplify the analysis, these 35 will be combined into five main categories. These pavement areas are shown below followed by the appropriate category codes:

1. Aircraft Operations (111111 - 116672): Runway, Apron, Arm/Disarm Pad, Power Check Pad, Wash Rack, Helicopter Pad, etc.

2. Equipment Storage (132133, 852273): AGE Storage, Other Equipment, etc.

3. Open Storage (451134 - 452775): BCE Holding Area, Base Supply Storage, etc.

4. Vehicle Operations (851145 - 852271): Parking Lot, Driveway, Road, Refueling Area, etc.

5. Loading/Unloading (890152 - 890158): Cargo Ramp, Aerial Port Facility, etc.

Pavement Characteristics. Having established a system for categorizing the major areas of USAF pavement, the next issue will be to establish the major characteristics of a pavement type. There are of course a large number of characteristics that could be addressed. This research focuses on the following:

1. Smoothness: This characteristic is important from the perspective that aircraft and/or equipment must transit the pavement. Any more than a minor irregularity in surface smoothness could result in a comfort or safety problem.

2. Cost: This characteristic has impact on how much pavement will be constructed or maintained.

3. Construction Duration: The time required to place a new pavement may impact the operation of the base. For example, a three month project to replace the main apron may require temporary relocation of the aircraft.

4. Durability: This characteristic has primary impact on the maintenance requirements and therefore the life-cycle cost of the pavement.

5. Surface Texture: A pavement must offer sufficient roughness to provide tire friction without being so coarse as to cause displacement of the surface aggregate.

Survey. Having established both a means of pavement categorization and a set of key pavement characteristics, the two concepts will be combined in a survey to determine relative priority. This survey will be given to two groups.

It will first be administered to a small panel of Major Command (MAJCOM) Pavement Engineers. These individuals have perhaps the best perspective on the overall requirements of USAF pavements.

The second group to respond to the survey will be the students of the AFIT Pavements Engineering course. This time however the group will be selected from students with a higher level of pavement experience. The higher level of experience is necessary because this survey deals with judgement rather than facts.

This survey will contain two parts. The first part will consist of demographic questions. The second and key part will be a priority matrix. This matrix will plot pavement category against pavement characteristic. The

respondents will rank each characteristic for each category of pavement in order of priority. A copy of the survey is in Appendix B.

Analysis. The purpose of the second survey is to establish the relative importance of each pavement characteristic for each pavement area. A frequency of response analysis will be performed to determine this relative importance. The MAJCOM Pavement Engineer's responses will be weighted twice those of the students due to the higher level of expertise at MAJCOM. A mean value and a standard deviation will be generated for the response in each matrix position. From these values, a priority rank for each characteristic will be established for each pavement category.

The concept of pavement characteristic prioritization leads to the next objective.

Research Objective 4: Decision Support Model

Background. By the very nature of their profession, engineers are decision-makers. Although theory provides the basis, decision guides actually support many important choices. For example, a table of recommended floor joist sizes for various spans and loads significantly reduces an engineer's calculations. This research objective will result in a decision-making model to provide guidance on the use of RCCP in the Air Force.

Model. The model will be a decision table. The table will consist of a series of yes/no questions based on two

different sources of data. These sources will be the advantages and disadvantages of RCCP and the relative importance of USAF pavement characteristics. This information will come from the results of Research Objectives 1 and 3. The questions will be asked of each RCCP candidate project.

The questions will be designed to determine one or more characteristics of the candidate project. The decision table will be constructed to select projects with characteristics that accentuate RCCP advantages while minimizing disadvantages. It will also give preference to important USAF pavement characteristics as determined in the second survey.

The decision table will have two parts. The first part will focus on mandatory project characteristics. For example, a disadvantage of RCCP may be its low smoothness tolerance. Also, on the second survey, smoothness may have been determined to be very important. Based on this knowledge, a question on the first part of the table would place a limit on vehicle speed. Therefore, projects in areas of high vehicle speeds would be unacceptable for RCCP use.

The second part of the decision table will be questions to determine desirable but not mandatory characteristics. For example, an advantage of RCCP may be its ability to be placed quickly. Also, the second survey could have determined construction speed to be of relatively low

importance on USAF projects. Therefore, a question on this part of the table would determine the required construction speed of the candidate project. If construction speed is important, then RCCP projects would be seen as desirable. But since construction speed was rated low on the survey, this would be a non-mandatory characteristic.

Once the decision model is established, it will be validated by the results of the next research objective.

Research Objective 5: Implementation Schedule

Background. Having established a general background in RCCP, as well as a specific decision-making tool for individual pavement projects, the final objective will be to provide an actual list of recommended RCCP projects. This will serve as the validation step for the model developed in the previous objective. The list will come from the Programming, Design, and Construction (PDC), and the CECORS (Civil Engineering Construction Requirements System) databases.

Lead Command. For the purposes of this research, this list will be developed using data from only one Major Command. This allows for a concise and manageable source of information.

Strategic Air Command (SAC) was chosen for this "lead command" position. The decision was based on several criteria. First, SAC has the widest variance in base climate. This will provide pavement performance evaluation under different temperature and moisture conditions.

Second, several SAC bases are located in the northwest United States. The reader will recall that at present, most RCCP expertise is resident in that area.

Third and finally, the SAC staff has at present both the experience and desire to support an RCCP development program. Taken together, these attributes support the choice of SAC as lead command.

PDC/CECORS. PDC is the electronic database of all Military Construction Program (MCP) projects either planned or currently under construction. CECORS is the database containing Operation and Maintenance (O&M) projects. An inquiry will be made through the SAC PDC/CECORS to assemble potential RCCP projects. Using the category codes listed in Research Objective 3, a compilation of potential MCP and O&M projects will be obtained. The vital statistics of these projects will come both from PDC and from the backup project data sheets (DD Form 1391).

Model Validation and Feedback. Once a list of potential projects have been assembled, each project will be processed through the decision model. At this point, any required adjustment to the model will be accomplished.

Once the final version of the model is established, the potential SAC RCCP projects will once again be processed through the model to arrive at a final RCCP project implementation schedule. This final version of the decision model will then be available to support design decisions for other USAF MAJCOMs.

Methodology Summary

This research project will answer the question of how the USAF may implement RCCP. The research is based on five objectives. The first two establish background. The third establishes USAF pavement requirements. The fourth builds a decision model, and the fifth validates the model with actual USAF project information.

This methodology leads to the next chapter where research results and analysis are discussed.

IV. Research Results and Analysis

Overview

This chapter presents results and analysis of the research outlined in the methodology of Chapter 3. These results will be organized in five sections corresponding to the five Research Objectives. First in line are the advantages and disadvantages of RCCP.

Research Objective 1: Advantages and Disadvantages of RCCP

The literature addresses many advantages and disadvantages of Roller Compacted Concrete Pavement. The following list is a non-hierarchical summary. References for each of the advantages and disadvantages can be found in Appendix C.

Advantages.

1. Low construction cost
2. Wide range of usable aggregates
3. Shorter haul distance (corollary to 2).
4. Fewer environmental impact statements required due to less need for new aggregate pits (correlary to 2)
5. Uses less cement than PCC
6. Rapid placement
7. Small construction crew
8. No formwork or paving trains required
9. Hand finishing not required
10. Resistivity to chemical attack
11. Long-term durability

12. Lower maintenance costs (corollary to 11)

13. Negligibile rutting or creep under long-term heavy loading

14. Constructed with existing asphalt construction equipment

15. Asphalt contractors interested in learning about RCCP

16. Strength gain with age

17. Recommended for areas with high strength requirements and low vehicle speeds

18. Minimizes impact of rainfall on construction process (corollary to 6)

19. Relatively thin mat thus minimizes disruption of buried utilities

20. Placement not sensitive to temperature

Disadvantages.

1. Smoothness difficult to achieve

2. Ravelling of joints

3. Not easily placed around appurtenances such as manholes and drainage inlets

4. Not easily placed in restricted areas

5. Contractor education required

6. Shrinkage cracking

7. Not robust to design and construction deficiencies

8. Not robust to lack of qualified quality control personnel and program

9. New technology

10. Pavements require cure period prior to use

Analysis. This list establishes the strong and weak characteristics of RCCP. The reader will note that some of

the characteristics tend to offset one another. For example, the fact that contractors are interested in learning about RCCP may be offset by the need for these contractors to learn the new technology. These characteristics will form the foundation for the the decision model of Research Objective 4.

Background information on USAF use of RCCP is developed in the next objective.

Research Objective 2: Present Knowledge Level

Background. This objective was designed to determine the level of general and specific knowledge USAF Pavement Engineers have on the subject of RCCP. The reader will recall that the tool to achieve this objective was a survey of students attending the AFIT Pavements Engineering class at Wright Patterson AFB, OH. The reader is reminded that the small number of respondents on this and the second survey do not support generalization.

Data. The frequency of occurence data for each question is presented in Tables VII-XIV:

TABLE VIII

Respondents' Current Station

Value	Frequency	Percent
CONUS..............................	27	84
USAFE..............................	2	6
PACAF..............................	1	3
Other..............................	2	6

TABLE IX

Respondents' Grade

Value	Frequency	Percent
O-1................................	6	19
O-2................................	8	25
O-3................................	1	3
GS-7...............................	1	3
GS-11..............................	8	25
GS-12..............................	5	16
GS-13..............................	1	3
Other (Foreign Students)............	2	6

TABLE X

Respondents' Years of Pavement Design Experience

Value	Frequency	Percent
0-1	14	44
1-2	8	25
2-4	6	19
More than 4	4	13

TABLE XI

Respondent Has Heard of RCCP?

Response	Frequency	Percent
Yes	24	77
No	7	23

TABLE XII

Respondents' Level of Expertise With RCCP

Value	Frequency	Percent
No expertise.........................	9	28
Minimal expertise....................	18	56
Some working knowledge...............	5	16
Well acquainted......................	0	0

TABLE XIII

Respondents' Perceived Competence To...

Activity	Frequency	Percent
Design an RCCP project?		
Yes............................	1	3
No.............................	31	97
Evaluate an A&E RCCP proposal?		
Yes............................	2	6
No.............................	30	94
Evaluate a contractor's Value Engineering RCCP proposal?		
Yes............................	1	3
No.............................	30	97

TABLE XIV

Respondent Knows LEE Policy on RCCP?

Response	Frequency	Percent
Yes................................	7	22
No.................................	25	78

Analysis. There are no surprises in the demographic information (Tables VII - XIV). Most (84%) of the respondents came from the CONUS. The highest percentage (85%) of respondents are Lieutenants and GS-11/12's. The majority (69%) have between 0 and 2 years of pavement design experience. This is a fair representation of the Design Section at most USAF bases.

It is apparent from the data that most (77%) USAF Pavement Engineers have heard of RCCP. This is corroborated by the next question in which most (56%) of the respondents identify with a minimal knowledge level built on a few magazine articles. A somewhat higher than expected number (16%) respond that they have actually seen an RCCP project being constructed. The surveys show that these respondents have a higher than average experience level.

The level of perceived competence (with respect to RCCP) of the Pavement Engineers is very low. By far, the majority do not feel competent to either, design an RCCP project (97%), evaluate a contractor's Value Engineering

proposal (94%) or to evaluate an Architect/Engineer design (97%).

A final interesting note is that the majority (78%) of these Pavement Engineers did not know of Colonel Klingensmith's 22 April 1985 letter recommending USAF development projects using RCCP.

The first two objectives established background by looking at the advantages and disadvantages of RCCP as well as at Pavement Engineer knowledge. The next objective will be to establish USAF pavement characteristics.

Research Objective 3: USAF Pavement Characteristics

Background. This objective investigated the priority of various pavement characteristics for various pavement areas on an air base. The tool to achieve this objective was a survey. The survey was given to a small number (3) of MAJCOM Pavement Engineers, and a small number (7) of the more experienced students in the AFIT Pavement Engineering class. Complete generalization is impractical with this small number of respondents. However, the data offers some trends that will be of interest in the final two Research Objectives.

Demographic Data. The frequency of occurence data for the demographic questions is presented in Tables XV-XVII.

TABLE XV

Respondents' Level of Assignment

Response	Frequency	Percent
Base	3	30
MAJCOM	7	70

TABLE XVI

Respondents' MAJCOM

Response	Frequency	Percent
SAC	2	20
TAC	1	10
AFLC	2	20
MAC	1	10
ATC	2	20
Space Command	1	10
AFSC	1	10

TABLE XVII

Respondents' Years of Pavement Experience

Value	Frequency	Percent
0-1	1	10
1-2	3	30
2-4	0	0
4-10	1	10
More than 10	5	50

Analysis of Demographic Data. The level of assignment data shows that although only three of the ten (30%) respondents were MAJCOM Pavement Engineers, seven of the ten (70%) were assigned at the MAJCOM level. This is because at MAJCOM level there may be more than one engineer working on the pavement program. However, only one (generally the senior and most experienced) engineer is assigned as the command Pavement Engineer.

The fact that seven MAJCOMs are represented in the survey data gives breadth and scope to the results. The reader will note that three major types of flying mission (strategic, tactical, and cargo) are represented as well as various support missions.

The requirement for mature judgement is supported by the level of pavement experience. Half of the respondents have more than ten years of experience.

Having now reviewed the demographics, the next issue is the relative pavement priority data.

Priority Data. The survey requested each of the respondents to rank-order each column (pavement area) from highest to lowest priority (1 for highest, 5 for lowest) for each pavement characteristic. The reader is encouraged to review the detailed explanation of the terms used in the survey (Appendix B). The mean values and standard deviations for each matrix position are contained in Appendix D. The resulting rank orders are shown in Table XVIII.

TABLE XVIII

Respondents' Ranking of Pavement Attribute vs. Pavement Area

	Pavement Type									
	Aircraft		Equip		Open Sto		Vehicle		Load/Unload	
Attribute	New	Repl	New	Repl	New	Repl	New	Repl	New	Repl
Smoothness	2	2	3	3	3	4	3	3	2	2
Cost	*3.5	4	2	2	2	1	1	2	3	3
Constr Durat	5	3	5	4	5	3	5	4	5	4
Durability	1	1	1	1	1	2	2	1	1	1
Surface Text	*3.5	5	4	5	4	5	4	5	4	5

* tie

When all the mean values of all types of pavement areas are averaged, the overall attribute ranking is as shown in Table XIX.

TABLE XIX

Respondents' Ranking of Pavement Attributes for All Areas

Attribute	Rank
Smoothness.................................	3
Cost.......................................	2
Costr Duration.............................	5
Durability.................................	1
Surface Text...............................	4

Analysis of Priority Data. Three issues are apparent from the above data. First is the fact that the relative attribute priority changes among pavement types. For example, cost on a replacement aircraft pavement is rated fourth in priority while cost on a replacement open storage area is rated first. The second issue is that the relative attribute priority changes within an area depending on whether the project is new work or replacement. For example, in every case construction duration for a replacement project is rated more important than for a new project.

Finally, it is apparent from the data that the respondents are taking a long-term view of relative

attribute priority. For example, in every case durability (a long-term characteristic) is rated more important than construction duration (a short-term benefit).

Having now established a system for ranking the relative priority of various pavement characteristics in various areas, the next task is to assemble a decision model to incorporate this information.

Research Objective 4: Decision Support Model

Background. The purpose of this model is to provide a means of structuring the engineer or engineering manager's decision as to whether or not a project should be allowed alternate bids using RCCP. The reader will recall that the model is designed to select candidate USAF projects that accentuate the advantages of RCCP while minimizing the disadvantages. It does this while giving preference to projects with characteristics seen as important by USAF Pavement Engineers.

Model. The model is a decision table consisting of several questions. The model is purposely simple to encourage widespread use. It incorporates two levels of questions. The first level establish mandatory project characteristics. The second level of questions concern optional but desirable characteristics. Together they help separate projects that would conceivably perform well with RCCP. As with all engineering decisions however, engineering judgement must be used on a case-by-case basis. The model is shown in Table XX.

TABLE XX

RCCP Decision Support Model

INSTRUCTIONS: As you review EACH project, mark the appropriate response for each question.

Question:	Yes	No
1. Does this project include an area greater than 15,000 square yards?.....	____	____
2. Does this project support vehicle or aircraft speeds less than 25 mph?.....	____	____
3. Does this project have a design slope of one percent or greater?...........	____	____
4. Is this project in a non-restricted area (i.e. not in an enclosed area with little access for construction equipment)?..........................	____	____
5. Is this project in an area with no significant appurtenances (i.e. manholes, storm drain inlets, etc.)?..	____	____
6. Does the area survey show contractor bid interest in RCCP?................	____	____
7. Is the specified surface tolerance equal to or greater than 1/4 inch in 10 feet?.................	____	____
8. Is a screed-quality surface finish acceptable?.........................	____	____

INSTRUCTIONS: Questions 1-8 establish mandatory criteria for use of RCCP. If you answered "no" to any of the above eight questions the project is not recommended for an RCCP alternate bid. If you answered "yes" to all the above questions, proceed with the following:

9. Is this a replacement project?........	____	____
10. Is the Current Working Estimate (CWE) within 10% of the Programmed Amount (PA)?.........................	____	____

11. Are experienced (in RCCP) inspectors and a certified independent testing laboratory available in-house or by contract?............................ _____ _____

12. Is this project in an area with a restricted outdoor construction season or in a frost susceptible area?................................. _____ _____

INSTRUCTIONS: Questions 9-12 establish desirable but non-mandatory criteria for use of RCCP. Preference should be given to projects with the largest number of "yes" answers for questions 9 through 12. Projects with few or no "yes" answers to these questions may still successfully use RCCP. However, engineering judgement should be carefully exercised in these cases.

Analysis. The reader will note that the decision model accentuates the advantages of RCCP while minimizing the disadvantages. It also reflects the priority information gathered from the USAF pavement characteristic survey. An amplification of each question in the model is presented below.

Minimum Area. A minimum pavement area of 15,000 square yards was established. This was based on the pavement experience described in the Literature Review of Chapter 2. The more successful projects were those in which the project was large enough to allow the contractor to reach a relatively high level of proficiency. Smaller projects do not allow this learning process.

Aircraft/Vehicle Speed. RCCP is difficult to place to extremely exact surface smoothness tolerances.

Therefore, high aircraft or vehicle speeds are not recommended on RCCP.

Slope. In order not to construct "bird baths" (surface depressions) a minimum slope of one percent was chosen. Pavements with slopes less than this are difficult to construct accurately. Also, a one percent slope was specified on the Portland International Airport (PIA) project.

Area Restrictions. Because a full asphalt "paving train" is required, RCCP is difficult to place in restricted areas. Equipment must have relatively free access in order to keep up the high placement rate.

Appurtenances. It is possible to construct RCCP in areas with appurtenances. In most cases, these structures are built up to the top of the base course, marked, and paved over. They are later sawn out when laydown is complete.

Contractor Interest. The PIA project showed the value of a survey of area contractor interest. They found several contractors to be receptive to an RCCP alternate bid. Most engineers perform this survey prior to any unusual design. This step must be accomplished in order to assure responsive alternate bids on RCCP.

Smoothness. This subject was explained during the discussion on aircraft and vehicle speed. It should be noted that the Corps of Engineers Guide Specification for RCCP limits smoothness to 3/8 inch in 12 feet. The PIA

project specified a smoothness of 1/4 inch in 10 feet. These values are not extremely different and the more stringent value was chosen for this model.

This completes the description of the mandatory project characteristics. Next are the desirable features.

Replacement. The pavement priority survey indicated that a short construction duration was more desirable on replacement projects than on new work. Since one of the main advantages of RCCP is its quick placement, the preference for replacement projects accentuates this postive characteristic.

Current Working Estimate (CWE). Another RCCP strong point is its lower unit cost. The ratio of CWE to Programmed Amount (PA) is a means of determining cost sensitivity in a USAF project. If the ratio is low (near .7 for example), cost is not very critical. However if the ratio is .9 or higher the cost is critical. This ratio is not the only means of determining cost significance. Cost savings on any project are significant. However, use of this ratio in the decision model allows an objective view of cost criticality on USAF projects.

Inspectors. Most authors agree that RCCP is not very robust to deviations from proper design and placement. Therefore, it is critical that an adequate inspection and testing system be available.

Construction Season. A positive characteristic of RCCP is its ability to be placed in cold climates and in

frost susceptible areas. Consequently, the decision model gives preference to projects with these characteristics.

This completes the discussion of the decision support model. The fifth and final Research Objective validates this model using SAC project information.

Research Objective 5: Implementation Schedule

Background. This final objective was designed to accomplish two things. First, it was to validate the decision model presented in Research Objective 4. Second, it was to establish a recommended schedule of RCCP projects.

The reader will recall that Strategic Air Command was chosen as lead command for the purposes of this Research Objective. A trip to the Engineering and Services (DE) Directorate of Headquarters SAC, Offutt AFB Nebraska provided the data to achieve this Research Objective. The DE staff at SAC proved invaluable in assembling this data. While at HQ SAC, two additional data constraints were established to aid in data managibility. These were the selection of test bases and the establishment of an earliest allowable program year for projects.

Selection of Test Bases. Two issues were considered in the selection of test bases. These were climate and the number of pavement projects programmed at each base.

Climate. One of the main reasons SAC was chosen as lead command was the wide variance of climatic conditions available at the 25 SAC bases. The wide climate

variance at these SAC bases allows a thorough evaluation of RCCP performance.

Number of Pavement Projects. Another selection criteria for the test bases was their pavement program. A cursory review of the pavement projects contained in the MCP and O&M programs at several bases showed some bases without a wide selection of pavement projects. These bases were not considered as test bases.

Five bases were chosen as test locations. These bases were:

1. Blytheville AFB, AR
2. Dyess AFB, TX
3. Fairchild AFB, WA
4. Minot AFB, ND
5. Pease AFB, NH

These bases meet both criteria. They represent a varied climate and have a reasonable number of potential RCCP projects. Figure 6 shows the widespread locations of the bases, and Table XXI confirms the large variance of the climatic conditions.

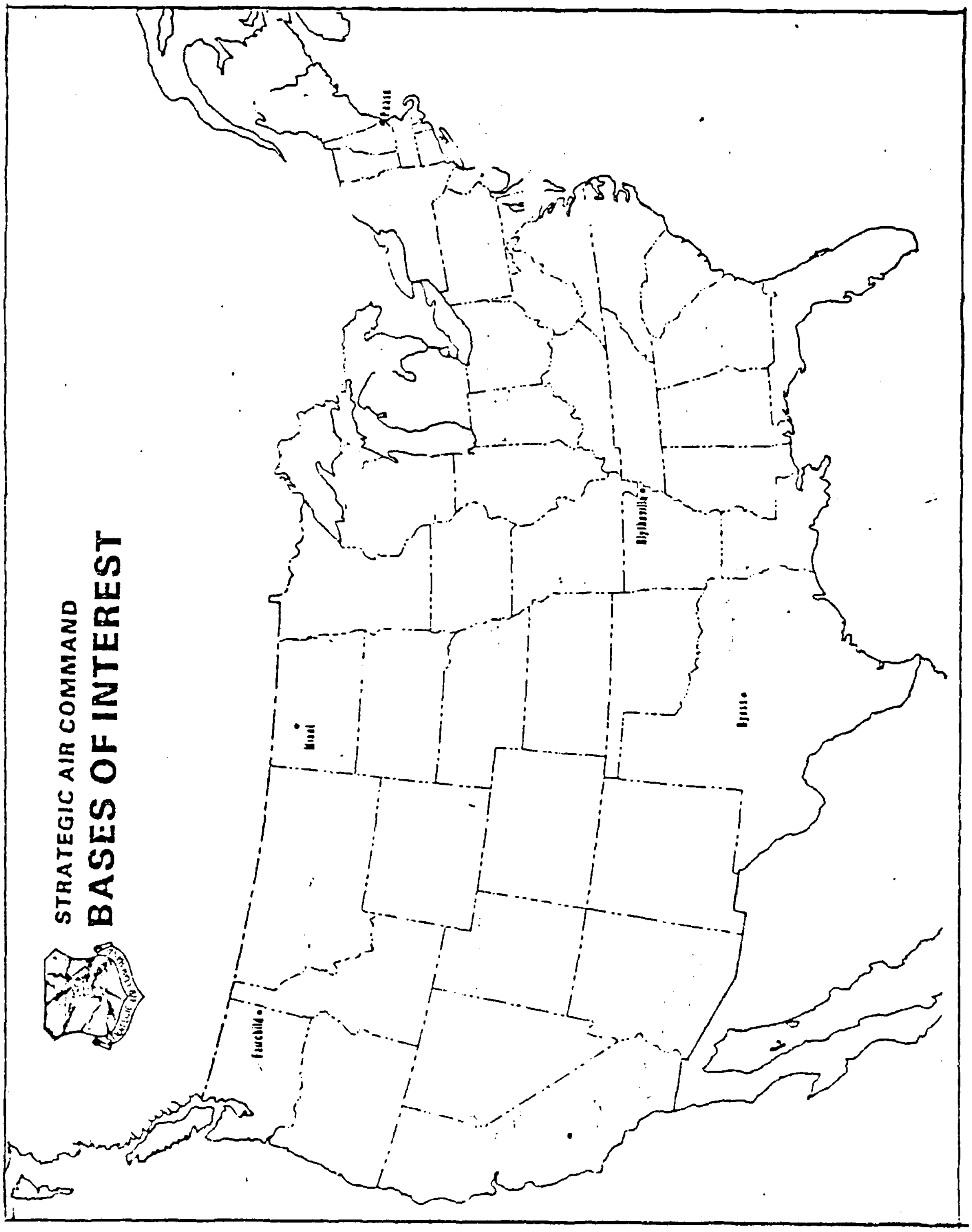

Figure 6. RCCP Test Bases

TABLE XXI

Climatic Conditions at Six SAC air bases (9)

	Climatic Parameter					
Base	Total Precip (in/yr)	Temp Jan Hi/Lo (deg F)	Temp Jul Hi/Lo (deg F)	Humid % at (0400/ 1300)	Days of Rain > 0.01 in	Days of Snow > 0.01 in
Blytheville	49.7	43/28	90/71	80/58	106	7
Dyess	24.7	55/32	94/73	68/45	65	2
Fairchild	15.6	30/21	82/57	74/54	107	35
Minot	17.0	13/-4	82/57	73/54	95	40
Pease	43.9	32/16	80/61	77/56	127	33

The second of the additional data constraints added to the Methodology during the trip to HQ SAC was program year.

Program Year. When a project requirement is established at an air base, that project is prioritized and placed in a program year. For example, an additional apron may be required at Pease AFB. It is important but not critical. The base may choose therefore to place this project in its fiscal year (FY) 1989 construction program. The choice of a fiscal year for project accomplishment establishes project milestones. In this case, the FY 89 apron project would be designed in FY 88, advertised and awarded in FY 89.

With this in mind, it was decided to review projects in programs no earlier than the FY 88. This restriction allows

a time for a comprehensive review of each project's potential for RCCP use. It also avoids recommending modifications to projects already under design.

Once these two additional data constraints were established, the data was ready for project pre-selection.

Pre-selection. Limiting the number of test bases reduced the number of potential projects. However, many projects were obviously unsuitable. The reader will recall that the decision model rejects pavement projects that do not accentuate the positive characteristics of RCCP while minimizing its negative characteristics. In project pre-selection, these same characteristics were kept in mind. For example, one rejection criteria was vehicle speeds in excess of 25 mph. Therefore, projects with titles such as "Replace Runway" were not included in the list of potential projects.

In review, three criteria needed to be satisfied for a pavement project to be considered for RCCP using the decision model. First, it needed to be at one of the five selected bases. Second, it needed to be in the FY 88 program or later. Third, its title must not have indicated violation of one of the decision model criteria. Using these criteria, 48 projects were selected for review. Of these, 11 were from the MCP and 37 were from the O&M program.

It should be noted that the automated PDC search technique described in the Methodology of Chapter 3 was not

yet fully operational at HQ SAC. Projects were not coded by category codes and the O&M projects were not included in the database. Therefore, an automated project search was not possible. The 48 projects mentioned above were hand-sorted. However, the methodology described in Chapter 3 will be valid once the database is fully integrated as planned.

Results. Table XXII shows the results of the review of each project. Before reviewing these results, the reader is encouraged to review the decision model as presented in Research Objective 4.

TABLE XXII

Results of Project Review

Proj No.	Description	Recommendation	Comments
Blytheville			
86-0091	Aircraft Apron Extension	Accept	MCP (FY 90)
89-0093	Transient Aircraft Apron	Accept	MCP (FY 89)
89-0100	Expand Alert Parking	Reject	Irregular shape
89-0097	Base Civil Engr Complex	Reject	Area less than 15,000 sy
88-0010	Repair Pvmt Ops Area	Reject	Area less than 15,000 sy
88-0017	BCE Storage Shed	Reject	Area less than 15,000 sy
88-0026	CE Parking Lot	Reject	Area less than 15,000 sy
89-0010	Repair Operational Apron	Reject	Area less than 15,000 sy
90-0014	Overlay Apron Road	Reject	Speeds greater than 25 mph
92-0010	Repair Ops Apron	Reject	Individual slab repairs
92-0011	Repair Access Taxiway	Reject	Individual slab repairs

Dyess

87-3002	Vehicle Maint Shop Addn	Reject	Area less than 15,000 sy
88-3002	Add to B-1 Engine Maint	Reject	Area less than 15,000 sy
88-0020	Sqdn Ops Parking Lot	Reject	Area less than 15,000 sy
92-0012	Veh Maint Parking Lot	Accept	O&M (FY 90)

Fairchild

87-2500	Alert Aircraft Parking	Reject	Irregular area
87-0015	Addtnl Aircraft Apron	Reject	Irregular area
88-0031	Light Duty Maint Ramp	Reject	Crack maintenance
88-0033	Pave Hvy Dty Maint Ramp	Reject	Crack maintenance
89-0006	Repl Barrier Cable Pvmt	Reject	Requires formwork
89-0019	Repr Tanker Alert Ramp	Reject	Crack maintenance
89-0022	Overlay Sewage Plnt Road	Reject	Speeds greater than 25 mph
89-0034	Repair Misc Taxiways	Reject	Crack maintenance
89-0043	Repair Fuel Truck Parking	Reject	Area less than 15,000 sy
90-0005	Recycle Taxiway and Apron	Accept	O&M (FY 90)
90-0011	Repair Nosedock Pvmt	Reject	Area less than 15,000 sy
90-0012	Rpr Bomber Alert Area	Reject	Crack maintenance
90-0020	Concrete Pad Wherry	Reject	Many small areas
90-0024	Surface Parking Lot	Reject	Area less than 15,000 sy
91-0001	Repair Road	Reject	Speeds greater than 25 mph

Minot

87-0046	Maint Apron Addtn	Accept	MCP (FY 89)
88-0001	Rpr PCC Slabs Apron	Reject	Individual slab repairs
88-0042	Recycle Airfield Pvmts	Reject	Speeds greater than 25 mph
88-0050	Recycle Roads	Reject	Speeds greater than 25 mph

88-0053	Pave Access Roads	Reject	Speeds greater than 25 mph
88-0075	Construct Open Storage	Reject	Area less than 15,000 sy
89-0038	Construct Road	Reject	Area less than 15,000 sy
89-0041	Recycle Airfield Pvmts	Reject	Speeds greater than 25 mph
90-0010	Maint TAC Aprons	Reject	Crack maintenance
90-0011	Maint R/W & Warmup Aprons	Reject	Crack maintenance
90-0012	Maint Taxiways	Reject	Crack maintenace
90-0014	Recycle Airfield Pvmts	Reject	Speeds greater than 25 mph
Pease			
87-1113	Maint Dock Fuel Cell	Reject	Smoothness > 1/4 in
88-1104	Widen Taxiway Alert Area	Reject	Speeds greater than 25 mph
86-1004	Veh Ops Heated Parking	Reject	Area less than 15,000 sy
88-0001	Repl Pkng Apron (Ph 1-5)	Accept	O&M (FY 88)
91-0005	Replace Warmup Pad	Reject	Slab maintenance
92-0006	Repalce Slabs Apron B	Reject	Slab maintenance

Analysis. The analysis of the project selection process can be divided into two categories. First is the resulting project list and second is the adjustments made to the decision model. First to be addressed is the recommended project list.

Recommended Projects. Six of the potential 48 projects were selected by the decision model for recommended use of RCCP. Three of the six are MCP. It is interesting to note that there is at least one project per base. Five of the six projects are aircraft aprons. This is not

surprising considering the minimum area restriction of 15,000 square yards.

Another interesting observation is the programmed year for each of the selected projects. The first scheduled project is the Pease AFB parking apron, scheduled as a five year phased replacement to begin in FY 88. Following that project are the Minot apron expansion and the Blytheville apron addition in FY 89. The remaining three projects are scheduled in FY 90. This one-two-three per year progression is a good development schedule for a new technology.

Having now established a project list, the final issue to be addressed is the adjustment of the decision model.

<u>Decision Model Adjustments</u>. As the project selection process proceeded, several modifications to the 12 questions in the decision model became advisable. They are each discussed below.

<u>Appurtenances</u>. The restriction of RCCP to areas with no "significant" appurtenances was vague. For example, several SAC apron projects were to be constructed with underground fuel hydrants. If no appurtenances were allowed, these projects would be rejected. As developed in the Literature Review of Chapter 2, the normal way to deal with appurtenances is to pave over the stubs and later saw out the needed access area. That area is later filled with PCC. There is no reason why this technique could not be used for fuel hydrants and other newly installed

appurtenances. Therefore, the language of this question was clarified.

Area Contractor Interest. An informal telephone survey of the Pavement Engineers at the five test bases showed that only one, Fairchild AFB WA, showed any local contractor interest in RCCP. The restriction of RCCP to areas showing present interest seemed unduly restrictive, especially considering the fact that most of the recommended projects would not begin until FY 89. Therefore, this question was moved from the mandatory criteria section to the desirable criteria section.

Shape of Pavement Area. Several of the projects reviewed were in irregularly shaped areas. For example, two bases wanted to pave around the aircraft alert "stubs" immediately adjacent to the runway. This type of area does not lend itself well to RCCP. This is because of equipment restrictions. The RCCP "paving train" consists of the asphalt machine, dump trucks, and rollers. It is difficult for this equipment to negotiate tight spaces or short radius curves. Therefore, with these considerations in mind, an additional question dealing with area shape was added.

Current Working Estimate. The use of only FY 88 or later projects precludes the use of cost data. This is because CWE's are not developed until design is begun. Therefore this question was withdrawn.

Inspectors. The availability of a certified testing lab can be assumed at all locations studied. Since RCCP experience is so limited (re: the telephone survey) the desire for inspectors with RCCP experience was seen as unduly restrictive. This question also was withdrawn.

Using the above modifications, the revised decision support table is shown in Table XXIII.

TABLE XXIII

Revised RCCP Decision Support Model

INSTRUCTIONS: As you review EACH project, mark the appropriate response for each question.

Question:	Yes	No
1. Does this project include an area greater than 15,000 square yards?.....	____	____
2. Does this project support vehicle or aircraft speeds less than 25 mph?.....	____	____
3. Does this project have a design slope of one percent or greater?............	____	____
4. Is this project in a non-restricted area (i.e. not in an enclosed area with little access for construction equipment)?........................	____	____
5. Is this project a rectangular, or a series of rectangular areas?..........	____	____
6. Is this project in an area with no existing, immovable appurtenances (i.e. manholes, storm drain inlets, etc.)?..	____	____
7. Is the specified surface tolerance equal to or greater than 1/4 inch in 10 feet?..................	____	____
8. Is a screed-quality surface finish acceptable?..........................	____	____

INSTRUCTIONS: Questions 1-8 establish mandatory criteria for use of RCCP. If you answered "no" to any of the above eight questions the project is not recommended for an RCCP alternate bid. If you answered "yes" to all the above questions, proceed with the following:

9. Is this a replacement project?........ _____ _____

10. Does the area survey show contractor bid interest in RCCP?................. _____ _____

11. Is this project in an area with a restricted outdoor construction season or in a frost susceptible area?................................ _____ _____

INSTRUCTIONS: Questions 9-11 establish desirable but non-mandatory criteria for use of RCCP. Preference should be given to projects with the largest number of "yes" answers for questions 9 through 11. Projects with few or no "yes" answers to these questions may still successfully use RCCP. However, engineering judgement should be carefully excercised in these cases.

Summary of Results and Analysis

This chapter presented the results and analysis of five Research Objectives. Research Objective 1 provided a list of the advantages and disadvantages of RCCP. Research Objective 2 established that only a small group of USAF Pavement Engineers have a working knowledge of RCCP. It also showed that these individuals do not feel technically qualified to evaluate an RCCP project. Research Objective 3 established a matrix of important pavement characteristics for various areas of USAF pavements. Research Objective 4 incorporated the results of Research Objectives 1 and 3 into

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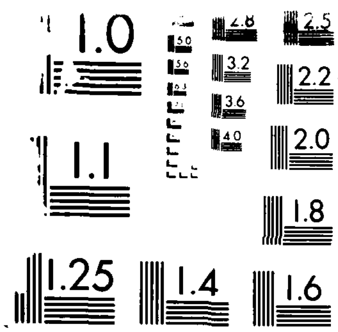
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

a decision support model for selection of candidate RCCP projects. Finally, Research Objective 5 validated the decision support model and provided a recommended implementation schedule using five SAC bases.

The next and final chapter provides a research summary, research conclusions, and a list of recommended further actions.

V. Summary, Conclusions, and Recommendations

Summary

This research effort focused on U.S. Air Force pavement construction and maintenance. It began by introducing the scope of USAF pavements. The replacement value of these pavements is over 20 billion dollars. Half of the Air Force's 500 million square yards of pavement are beyond their design life. Together, these two facts provided the motivation to study possible improvements in USAF pavement construction and maintenance.

Having thus focused on the magnitude of the USAF paving program, RCCP was introduced as a potential construction and maintenance method. But how should the USAF view RCCP? The problem statement could be paraphrased as "there is a new paving method out there that seems faster and cheaper, so what do we do about it?".

Five Research Objectives were established to guide the study of the problem. These ranged from a very general survey of RCCP literature to very specific USAF RCCP action plan. The first Research Objective established the advantages and disadvantages of RCCP. The tool to accomplish this objective was a review of the literature. The Literature Review was built on two approaches. The first approach looked at RCCP from a functional approach. It studied RCCP design, mixing, placement and other processes. The second approach looked at RCCP from a case study approach. Six recent RCCP projects were reviewed to

bases. Six were selected. Based on the above research, these six projects would perform well using RCCP.

Conclusions

In concluding this study of RCCP, it is important to once again look at the Problem Statement. The problem is, "how can the USAF use RCCP?" This research has established several characteristics of RCCP that point strongly to its profitable use. Chief among these is low cost. An average cost savings of 15 percent below asphalt cement concrete is conservative. The implications of this magnitude of savings are significant. Using an estimated 15 percent savings on the six recommended RCCP projects would result in a savings to the USAF of approximately 12.7 million dollars.

RCCP is also quickly placed and strong. These and others are valuable characteristics, but they do not alone support immediate general use on all USAF concrete pavements.

RCCP has inherent weaknesses. Some of these will be improved with time, some will not. A significant weakness at present is the localized nature of RCCP expertise. Most experience has been gained in the Pacific Northwest. However, the literature shows a growing area of RCCP use. Having begun in Canada, several major projects have been constructed as far away as Houston, TX. The inherent low cost and ease of placement will establish RCCP's share of the pavement market in the next 2 to 5 years.

Another weak point is placement technology. Placement equipment specifically designed for RCCP is only just now being developed. A leader in the field is ABG of West Germany, although Barber-Greene is now beginning to market some American products.

Some of RCCP's weaknesses however will not be cured with time. The nature of RCCP placement precludes extremely high tolerances of smoothness and surface texture. This, for example, restricts RCCP from use on a aircraft hangar floor. Even with the improvements in equipment and placement methods, smoothness tolerances better than 1/4 inch in 10 feet cannot be expected. However, many other areas such as aprons, low-speed taxiways, parking lots and many others seem well suited to RCCP.

Another weakness of RCCP is its sensitivity to exact mixing, placement, and curing. The low water content does not allow much room for error. Therefore, an aggressive quality control program is essential. In the USAF, this QC program must be managed directly by the Base Civil Engineer's Construction Management Section.

This study uncovered some other interesting facts. The telephone survey of Pavement Engineers at the five test bases revealed some significant individual differences between bases. Minot AFB, for example, is close to several oil fields. This has resulted in ACC being much cheaper than PCC. This fact would no doubt effect the bid climate of a potential RCCP project at Minot. Another interesting

insight was the fact that many USAF bases are located in relatively small towns. New technologies do not thrive in remote areas. Consequently, contractor interest may be less at these locations than at bases closer to large metropolitan areas. These facts show that the individual differences of each base must be weighed with engineering judgement to determine if RCCP would be a logical alternative. This essential use of engineering judgement is emphasized in the decision model.

In conclusion, RCCP is a strong contender for a significant portion of USAF pavements. Using a methodical development strategy as outlined in this research, RCCP can become a strong asset to the USAF Pavement Engineer and the USAF pavement construction and maintenance program. As the technology continues to develop, the USAF will stand to benefit greatly from this simple yet effective pavement system.

Recommendations

Recommendations stemming from this research can be categorized into projects, further research, and other issues.

Projects. The six projects selected for potential RCCP use should be reviewed by the SAC Pavement Engineer and the respective base Pavement Engineers for alternative designs and bids using RCCP. This development schedule will allow for a maturing USAF pavement program while concentrating

expertise at a single Major Command. However, other MAJCOMs can and should recommend projects for RCCP use.

Further Research. The possible use of RCCP as an expedient method should be investigated. The extremely fast laydown of RCCP could make it a feasible construction method for ramps, taxiways, and even runways in areas of short to medium use. The low cost and general worldwide availability of the necessary constituents of RCCP could make it a strong addition to existing expedient methods.

Other Issues. The low knowledge level of USAF Pavement Engineers with respect to RCCP needs to be corrected. A solution to this may be the addition of one or more lecture hours on the subject of RCCP at the AFIT School of Civil Engineering's course on Pavement Engineering (ENG 550). In addition, RCCP should be introduced at the USAF Worldwide Paving conference, as well as at MAJCOM Paving Conferences.

The Decision Support Model developed as part of this research effort should be distributed via letter from the the Engineering and Services Center to the MAJCOM Pavement Engineers and in-turn to base Pavement Engineers. This information could prevent costly mistakes and promote significant cost savings.

Finally, the essential technical aspects of RCCP need to be communicated to all USAF Pavement Engineers. This could be accomplished by attaching a short technical summary of RCCP to the present RCCP Guide Specification. This will help mitigate the possibility that our Pavement Engineers

would receive a contractor's RCCP proposal before they have some working knowledge of the subject.

Appendix A: Background Survey

ROLLER COMPACTED CONCRETE (RCC) PAVEMENT BACKGROUND SURVEY

The following survey is to support an AFIT graduate level thesis project on U.S. Air Force use of Roller Compacted Concrete Pavement. Response is voluntary and anonymous. We appreciate your time.

1. Where are you currently stationed?

   ______ CONUS ______ Europe ______ PACAF ______ Other

2. What is your grade?

   ______ O-1 ______ O-2 ______ O-3

   ______ GS-10 ______ GS-11 ______ GS-12 ______ GS-13

3. How many years have you been involved with pavement design?

   ______ 0-1 ______ 1-2 ______ 2-4 ______ more than 4

4. Have you heard of RCC? ______ Yes ______ No

5. What is your level of expertise with RCC Pavements?

   ______ No expertise at all, I've never heard of it.

   ______ Only minimal knowledge, I've seen one or two magazine articles on the subject.

   ______ Some working knowledge, I've seen an RCC project being constructed.

   ______ I consider myself well acquainted with RCC.

6. At the present time, do you feel qualified to:

   a. Design a pavement using RCC? ______ Yes ______ No

   b. Evaluate an A&E project using RCC? ______ Yes ______ No

   c. Evaluate a contractor's Value Engineering proposal to use RCC? ______ Yes ______ No

7. Did you know that HQ USAF/LEE has issued direction to begin trial use of RCC pavements? ______ Yes ______ No

Appendix B: Pavement Priority Survey

ROLLER COMPACTED CONCRETE (RCC) PAVEMENT PRIORITY SURVEY

The following survey is to support an AFIT graduate level thesis project on U.S. Air Force use of Roller Compacted Concrete Pavement. Response is voluntary and anonymous. We appreciate your time.

BACKGROUND INFORMATION:

1. At what level are you presently assigned?

   _____ Base _____ MAJCOM _____ HQ USAF _____ Other (__________)

2. What major command do you represent?

   _____ SAC _____ TAC _____ MAC _____ AFLC _____ ATC

   _____ USAFE _____ PACAF _____ Other (___________)

3. What base do you represent? _________________________________

4. How many years pavement experience do you have?

   _____ 0-1 _____ 1-2 _____ 2-4 _____ 4-10 _____ more than 10

INSTRUCTIONS:

The following matrix is designed to allow you to tell us the importance of various pavement attributes for various pavement projects. For each column (i.e. for each type of project) please rank the attributes from most important to least important (1 = most important, 5 = least important). Of course, all the attributes are important. But for the purposes of this survey, please rank them. See reverse of this sheet for explanation of terms.

	Pavement Type									
Attribute	Aircraft		Equip		Open Sto		Vehicle		Load/Unload	
	New	Repl	New	Repl	New	Repl	New	Repl	New	Repl
Smoothness										
Cost										
Costr Duration										
Durability										
Surface Text										

EXPLANATION OF TERMS

Pavement Types:

Aircraft Operations:	Apron, Arm/Disarm Pad, Power Check Pad, Wash Rack, Helicopter Pad, etc.
Equipment Pads:	AGE storage, other equipment, etc.
Open Storage:	BCE holding areas, Base Supply storage, etc.
Vehicle Operations:	Parking Lots, Driveways, Roads, Refueling areas, etc.
Loading/Unloading:	Cargo ramps, Aerial Port facilities, etc.

Attributes:

Smoothness:	Deviation from true plane measured in fractions of an inch per ten feet.
Cost:	Overall in-place pavement cost.
Constr Duration:	Number of days from Notice To Proceed until Final Acceptance.
Durability:	Resistance to spalling, rutting, and other rigid pavement distresses.
Surface Texture:	"Tightness" of paving matrix on top surface of pavement.

Others:

New work:	A new pavement in an area where no previous operational pavement was located (e.g. an additional apron for a squadron of Air National Guard F-4's to be activated in six months, located in a previous open field where construction does not impact ongoing base operations)
Replacement:	A repair by replacement (or upgrade) of an existing pavement area (e.g. removal and reconstruction of an F-4 ramp, located in an operational area that impacts ongoing base operations (i.e. requires relocation of the F-4 squadron)).

Appendix C: Advantages and Disadvantages of RCCP With References

Advantages.

1. Low construction cost (37:429), (36:16), (1:5), (29:3), (52:9), (30:7).

2. Wide range of usable aggregates (32:11), (30:7).

3. Shorter haul distance (32:11) [correlary to 2].

4. Fewer environmental impact statements required due to less need for new aggregate pits (32:11) [correlary to 2].

5. Uses less cement than PCC (37:29).

6. Rapid placement (29:3), (26:7), (52:9), (49:16).

7. Small construction crew (37:429), (52:9).

8. No formwork or paving trains required (37:429), (52:9).

9. Hand finishing not required (52:9).

10. Resistivity to chemical attack (1:5).

11. Long-term durability (1:5).

12. Lower maintenance costs (1:5) [correlary to 11].

13. Negligibile rutting or creep under long-term heavy loading (1:5).

14. Constructed with existing asphalt construction equipment (37:429).

15. Asphalt contractors interested in learning about RCCP (1:5).

16. Strength gain with age (32:3).

17. Recommended for areas with high strength and low vehicle speeds (4:7).

18. Minimizes impact of rainfall on construction process (29:3) [correlary to 6].

19. Relatively thin mat thus minimizes disruption of buried utilities (29:3).

20. Placement not sensitive to temperature (29:3), (26:7).

Disadvantages.

1. Smoothness difficult to achieve (4:7), (27:429), (29:3).

2. Ravelling of joints (37:429).

3. Not easily placed around appurtenances such as manholes and drainage inlets (38:2)

4. Not easily placed in restricted areas (38:2)

5. Contractor education required (36:17), (52:9).

6. Shrinkage cracking (29:3).

7. Not robust of design and construction deficiencies (29:3).

8. Not robust to lack of qualified quality control personnel and program (38:4)

9. New technology (29:3).

10. Pavements require cure period prior to use (30:7).

Appendix D: Pavement Priority Survey Results

NOTE: The following figures reflect the priority rankings of each attribute for each pavement area. They are based on a survey of 10 individuals. Three of the individuals were command Pavement Engineers. Their judgement was considered more valuable and were weighted twice the other respondents, making the effective number surveyed equal to 13. The mean values were rank ordered in each column to produce the priority values shown in parentheses.

Type of Pavement (1 of 5): Aircraft Operations

	New		Replace	
Attribute	Mean Rank	Std Dev	Mean Rank	Std Dev
Smoothness	2.23 (2)	1.42	2.46 (2)	1.39
Cost	3.31 (3.5)	1.44	3.62 (4)	1.56
Constr Dur	4.08 (5)	1.12	2.69 (3)	1.18
Durability	2.08 (1)	1.12	2.31 (1)	1.18
Surface Text	3.31 (3.5)	1.11	3.92 (5)	1.19

Type of Pavement (2 of 5): Equipment Operations

	New		Replace	
Attribute	Mean Rank	Std Dev	Mean Rank	Std Dev
Smoothness	3.31 (3)	0.95	3.46 (3)	1.05
Cost	2.08 (2)	0.95	2.08 (2)	1.12
Constr Dur	4.31 (5)	0.85	3.85 (4)	1.21
Durability	1.38 (1)	0.77	1.62 (1)	0.87
Surface Text	3.92 (4)	1.04	4.00 (5)	1.08

Type of Pavement (3 of 5): Open Storage

	New		Replace	
Attribute	Mean Rank	Std Dev	Mean Rank	Std Dev
Smoothness	3.62 (3)	0.96	3.85 (4)	1.07
Cost	1.77 (2)	0.83	2.15 (1)	1.21
Constr Dur	4.31 (5)	0.85	3.54 (3)	1.33
Durability	1.46 (1)	0.52	2.85 (2)	1.72
Surface Text	3.85 (4)	0.99	3.92 (5)	0.95

Type of Pavement (4 of 5): Vehicle Operations

	New		Replace	
Attribute	Mean Rank	Std Dev	Mean Rank	Std Dev
Smoothness	2.77 (3)	0.73	3.00 (3)	0.82
Cost	2.00 (1)	1.08	2.31 (2)	1.38
Constr Dur	4.15 (5)	1.34	3.38 (4)	1.50
Durability	2.15 (2)	1.41	2.23 (1)	1.54
Surface Text	3.92 (4)	1.04	4.08 (5)	1.04

Type of Pavement (5 of 5): Load/Unload

	New		Replace	
Attribute	Mean Rank	Std Dev	Mean Rank	Std Dev
Smoothness	2.15 (2)	0.90	2.46 (2)	1.13
Cost	2.69 (3)	1.25	2.69 (3)	1.32
Constr Dur	4.62 (5)	0.77	3.85 (4)	1.57
Durability	1.92 (1)	1.26	2.00 (1)	1.08
Surface Text	3.62 (4)	1.04	4.00 (5)	0.91

All Types of Pavement

Attribute	Mean Rank	Std Dev
Smoothness	2.93 (3)	0.61
Cost	2.47 (2)	0.60
Constr Dur	3.85 (5)	0.56
Durability	2.00 (1)	0.44
Surface Text	3.85 (4)	0.23

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VITA

Capt Scott K. Borges was born on 24 August 1955 in Washington DC. He graduated from high school in Suitland, Maryland, in 1973. From there he attended the University of Maryland from which he received the degree of Bachelor of Science in Civil Engineering in May 1977. He was commissioned through the USAF ROTC program and received the award of Distinguished Graduate. His has held various Base Civil Engineering positions in both the Operations and the Engineering Design and Environmental Planning Divisions at McGuire AFB NJ, and at the USAF Academy CO. He has also been assigned as the Officer in Charge of the Civic Action construction team in Truk, Micronesia, as well as Construction Project Manager at King Khalid Air Base, Saudi Arabia. He is a registered Professional Engineer in the state of Colorado. He entered the Graduate Engineering Management program in May 1985. His next assignment will be as an Engineering Staff Officer at Headquarters USAF.

Next military address:

HQ USAF/LEEVX
Bolling AFB, DC 20332

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Thesis Chairman: John H. Morrill, Captain, USAF
Associate Professor of Civil Engineering

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This research project studied the possibility of Roller Compacted Concrete Pavement (RCCP) use by the United States Air Force. RCCP is a dry, zero-slump concrete paving mixture. The low cost, high strength, and quick placement of RCCP make it extremely attractive as an alternate construction and repair method for USAF pavements.

This project accomplished five objectives. First, a thorough review of the literature provided a list of the advantages and disadvantages of RCCP. Second, a survey determined the RCCP knowledge level of a small group of USAF Pavement Engineers. Third, another survey established the relative importance of certain pavement characteristics in various USAF pavement applications. Fourth, a decision support model was created to assist in the selection of candidate U.S. Air Force RCCP projects. Finally, using this model, the Strategic Air Command project database was searched to provide a list of recommended RCCP projects.

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